I. C. 6779 May 1934

UNITED STATES BUREAU OF MINES
SCOTT TURNER, DIRECTOR

INFORMATION CIRCULAR

THE IRON BLAST FURNACE

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BY

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THE IRON BLAST FURNACE[1]

By T. L. Joseph[2]

INTRODUCTION

The Bureau of Mines has been studying the blast furnace for a number of years and has published detailed reports on various phases of its investigations. Inquiries frequently received for information of a more general character than that given in the detailed reports have prompted the preparation of an information circular to cover in a general way the important features of the Bureau of Mines blast-furnace investigations.

SHAPE AND DIMENSIONS OF FURNACE

The modern blast furnace approximates a refractory-lined steel cylinder about 90 feet in height and 25 feet in diameter. It actually consists of a number of cylinders and truncated cones superimposed upon each other. The shape and dimensions of a modern furnace are shown in figure 1. The bottom section, commonly referred to as the hearth or crucible, is a cylindrical section about 12 feet high. Liquid metal and slag collect in this part of the furnace and are withdrawn at regular intervals; iron is removed at a level about 2 feet above the bottom of the furnace and slag at a level about 5 feet higher. Depending upon the size of the furnace, 40,000 to 75,000 cubic feet of preheated air per minute is introduced through from 10 to 16 tuyeres equally spaced around the periphery of the hearth.

The divergent cone above the crucible is called the bosh. Immediately above the bosh is a short cylindrical section. A long section, commonly termed the "shaft," is located above this short cylindrical section. The inward slope of the walls in this part of the furnace is called the batter. This slope varies from 0.75 to 1.25 inches in 12 inches. Many furnaces have a short cylindrical section near the top. The outward flare of the walls above the stock line extending to the level of the gas offtakes is a recent development to provide additional volume above the stock line. Measurements by the United States Bureau of Mines of gas velocities above the stock in one furnace showed an increase from 7.6 feet per second with the big bell closed to 250 to 300 feet per second when the big bell was lowered and the

1 The Bureau of Mines will welcome reprinting of this paper, provided the following footnote acknowledgment is used: "Reprinted from U. S. Bureau of Mines Information Circular 6779."

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stock was discharging into the furnace. This large increase in gas velocity as the charge moved into the furnace showed the need of more space when the big bell and the moving stream of stock occupied a large portion of the space above the stock during the short interval of charging. The upper part of the furnace is insulated with about 4 feet of fire brick, while in the lower part a thinner refractory wall is maintained by means of water-cooled blocks.

Essential Features of Process

The blast performs three major functions: Ore, coke, and limestone are preheated; the metallic oxides in the ore are deoxidized or converted into metal; and the resulting iron and slag are melted. Raw materials (ore, coke, and flux) are charged into the top of the furnace and descend countercurrent to large volumes of carbon monoxide and nitrogen, generated near the bottom of the furnace. As a result of the countercurrent principle gas with the lowest reducing power comes in contact with the more easily reduced higher oxides at comparatively low temperatures near the top of the furnace, and gas richest in carbon monoxide meets the ore in the final stages of reduction at lower levels in the furnace. This results in maximum utilization of the reducing power of the gases. In a similar way the cold materials entering the top of the furnace come in contact with the colder gas, which aids transfer of heat from gas to solids by maintaining the greatest possible thermal head between gases and solids.

Basic Principles of Modern Furnaces Same as in Early Furnaces

The present process for converting iron ore into cast iron is fundamentally the same as that developed by the ironmakers of central Europe about 1350. At that time comparatively high furnaces, built of masonry and similar in shape to present furnaces, began to supersede the short furnaces or forge furnaces in which a mixture of iron and charcoal was heated until a small quantity of pasty metal was obtained. This metal, which was very low in carbon and called wrought iron, was then forged into useful articles. Many improvements have been made in blast-furnace construction, in operation, and in the handling of materials since the first production of cast iron or metal containing enough carbon and other elements so that it could be cast into useful shapes.

Importance of Engineering Skill a Large Factor in Blast-Furnace Progress

The chemical analysis of raw materials and products has been very essential to blast-furnace progress, but the mechanical construction of the furnace, the shape of the furnace, the methods of handling and charging raw materials, the proper preheating of the charge, and particularly the slag and metal have attracted more attention among metallurgists than the chemical process of ore deoxidation. There are very good reasons for this. Every chemist will agree that it is necessary to get reacting substances in contact at required temperatures for chemical reactions to proceed. Contact between

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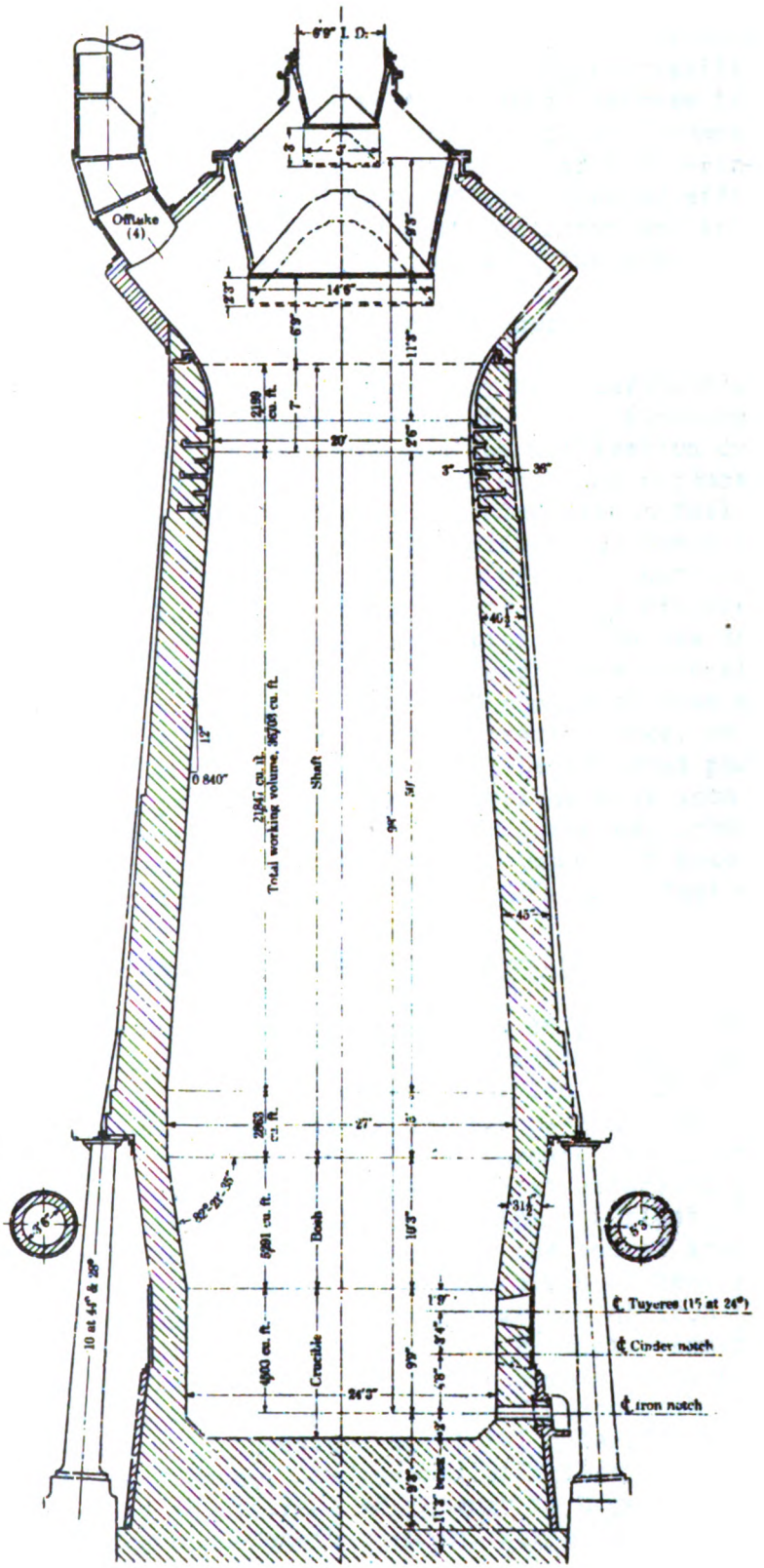

Figure 1.- Lines of modern blast furnace.

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iron ore and reducing agents can be obtained very easily on a small scale, and metallic iron can be produced at a fairly low temperature (950 C.). To produce pig iron in economical tonnages, however, engineering skill is necessary to provide on a large scale opportunity for contact between iron ore, coke, and limestone, and heated reducing agents. The blast furnace has survived because of its ability to produce large tonnages of iron economically. It is an economical piece of equipment because of its combined efficiency as a large-scale gas producer, as a large-scale heat generator and interchanger, as a large deoxidizing chamber, and as a large melting furnace.

Blast Furnace a Large Gas Producer

The various functions of the blast furnace may be understood more clearly if the process is considered from several points of view. Although the blast furnace is not operated primarily to produce gas for utilization outside of the process it may nevertheless be considered as a huge gas producer operated on preheated forced blast. If the furnace is operated with a fuel consumption of 1,700 pounds of coke per ton of iron, which implies good raw materials and good practice, about 120,000 cubic feet of gas are produced per ton of iron. As the quality of raw materials falls off the amount of gas produced per ton of pig iron increases very rapidly, and the operation approaches that of a slagging-type producer whose primary function is to produce combustible gases for use in other processes. For example, if 3,100 pounds of coke are required as a result of highly siliceous iron ore, inferior coke, or poor furnace practice, about 220,000 cubic feet of gas will be produced per ton of pig iron. The amount of gas produced per ton of iron depends upon the heat requirements for a given set of conditions. Modern furnaces, producing 1,000 tons of iron per day on a fuel consumption of 1,800 pounds of coke per ton of iron, will have a daily output of about 127,000,000 cubic feet of gas.

Blast Furnace a Large Heat Generator

The quantity of heat required to produce a ton of pig iron varies with the quality of the raw materials and the manner in which the furnace is operated. About 14,000,000 B.T.U. are generated per long ton of pig iron in American furnaces operating on Lake ores containing 51.5 percent iron and about 8.5 percent silica. In thermal studies of the blast furnace the general method has been to charge the furnace with the amount of heat generated per ton of pig iron, including the sensible heat introduced with hot blast; that is, the furnace is charged only for the heat generated per ton of iron and not for the total calorific value of the coke. On the basis of heat generated per ton of iron and heat consumed in the furnace per ton of iron the thermal efficiency of the blast furnace usually exceeds 80 percent. Inasmuch as the blast furnace is not primarily a heating furnace and must produce a highly reducing gas it hardly seems logical to charge the furnace with the total calorific value of the fuel. If, however, the total calorific value of the coke is charged against the furnace, its thermal efficiency is only about 60 percent. On such a basis the thermal efficiency is high when compared to that of other furnaces. The open-hearth furnace, for example, has a thermal efficiency of about 20 percent.

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Blast Furnace as a Heat Interchanger

The high thermal efficiency of the blast furnace is due largely to its efficiency as a heat interchanger and to low heat losses. The production of large volumes of carbon monoxide and nitrogen in the lower part of the furnace is accompanied by the evolution of a large amount of heat. This heat is liberated in such a small section of the furnace that high temperatures are attained. A small part of the heat is absorbed by the coke in the combustion zone and by the slag and metal passing through this zone. Most of the heat is carried to the upper part of the furnace as sensible heat of the gas stream. Transfer of heat from gases to solids occurs throughout a column about 70 feet high and 20 feet in diameter. The tortuous flow of gas through a portion of the voids in such a column of irregular solids provides intimate contact between gas and solid or a large number of "head-on" collisions between gas and solid. Heat losses are comparatively small because the ratio of the volume of the furnace to the external surface from which heat may be lost by radiation or water-cooling devices is small.

When the furnace is in operation the upper section is filled with particles of ore, coke, and limestone, which tend to retain their shape and size until the fusion zone is reached. Below the fusion zone coke alone remains in the solid form and supports part of the total weight of the stock above. About 1,800 tons of ore, 450 tons of limestone, and 800 tons of coke are charged daily into the top of a blast furnace capable of producing 1,000 tons of pig iron in 24 hours. This quantity of raw material is brought up to the temperature prevailing in the crucible of the furnace by being moved downward under the force of gravity countercurrent to about 120,000,000 cubic feet of gas reduced to standard conditions. This amounts to 18 cubic feet of gas per pound of charge.

The gases leave the combustion zone in the bottom of the furnace at a temperature of about 2,000° C. and gradually decrease in temperature as they ascend through the charge and give up their sensible heat to the charge. One cubic foot of gas generated at the tuyères carries only enough heat to bring 1 ounce of stock up to the temperature in the crucible; that is, the gas has a low heat capacity, but due to the fact that a very large amount of gas is passed through the charge the total transfer of heat is large. The large volume of gas involved in the process comes largely from the air, which is the largest single material both by weight and volume that enters the blast furnace. For example, a 1,000-ton furnace would use a total of about 3,000 tons of raw materials and about 3,600 tons of air in 24 hours.

Blast Furnace a Large, Vertical Chamber for Deoxidizing Iron Ore

The intimacy of contact essential for the transfer of heat from gases to solids which is obtained by the countercurrent circulation of gases and solids in the blast furnace is likewise a desirable feature in the large-scale deoxidation of iron ore. Highly heated as well as strongly reducing gases generated near the bottom of the furnace pass through a long vertical

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column of iron ore, coke, and limestone, the coke and limestone acting to some extent as spacers, which give the column permeability to gas flow. The primary function of the coke is to produce heat required in the process, while the limestone reacts with the earthy materials (silica and alumina in the ore) to produce a fluid slag that will flow readily from the furnace.

A modern 1,000-ton furnace consumes in 24 hours approximately 1,800 tons of ore containing about 400 tons of oxygen. The major part of this oxygen is removed from the ore by bringing it in contact with carbon monoxide gas, which at the prevailing temperature in the blast furnace removes the oxygen from the ore.

Operation of Process Behind Closed Doors

In normally operated furnaces the tuyère openings through which air is admitted afford the only opportunity for direct observation of conditions existing in the interior of the furnace. The furnace operator watches conditions he can see through the tuyeres very closely and changes his operation according to the analysis and temperature of the iron and metal tapped from the furnace. However, he is greatly handicapped by lack of information on the conditions between the stock line and the bottom of the furnace. In attempting to study the blast furnace the Bureau of Mines has focused attention upon ways and means of learning something about conditions in the interior of the furnace, upon laboratory studies to determine the relative resistance which various sizes of particles offer to the flow of gases, and upon factors that control the transfer of heat from gases to solids. The investigations into interior blast-furnace conditions have been conducted on an experimental blast furnace and upon commercial furnaces, while the other two problems have been studied in the laboratories of the North Central Experiment Station at Minneapolis. This line of study was prompted by the belief that information on conditions on the inside workings of a blast furnace would suggest means of improving the process, which involves the counterflow of gases and solids. To learn something about the pressure required to force gas through beds of irregular solids and to know the distribution of gas that would result from a given size distribution of solids it was necessary to conduct extensive laboratory experiments, because very little pertinent information was available. Similarly, fundamental information was needed upon the transfer of heat from gases flowing through beds of broken solids.

Combustion Zones in Front of Tuyères

The seat of life of the furnace is in the combustion zones in front of the tuyères, because the heat as well as the reducing gases for carrying on the process are generated in this part of the furnace. To determine the conditions in front of the tuyères under widely different conditions Perrott and Kinney[3] of the Bureau of Mines explored the combustion zones of some 13

3 Perrott, G. St. J., and Kinney, S. P., Combustion of Coke in the Blast Furnace: Trans. Am. Inst. Min. and Met. Eng., vol. 69, 1923, pp. 543-584.

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furnaces by means of water-cooled sampling tubes driven into the furnace through the tuyères.

Figure 2 shows the composition of the gases in the combustion zone and brings out a very important point that the active combustion zones are comparatively small. The curves show the change in gas composition at progressive distances from the nose of the tuyère in toward the center of the furnace. The tuyère is a water-cooled copper casting extending several inches in beyond the wall of the furnace. Zero distance corresponds to the face of the tuyère where the preheated air first strikes the fuel bed. The normal 21 per cent of oxygen in the air immediately drops to about 14 per cent. Gas occupying the space between coke lumps is presumably burned by the oxygen of the air. This is the most obvious explanation for the sudden drop in oxygen content. At progressive distances in toward the center of the furnace the oxygen content decreases until it practically disappears at about 30 inches. The carbon dioxide reaches a maximum about 25 inches from nose of the tuyère and falls off to practically zero percentage at 40 to 50 inches. The carbon monoxide increases very rapidly beyond 16 inches and reaches a maximum in the center of the furnace.

The composition of the gases at the tuyère level shows that preheated air is converted into carbon monoxide and nitrogen within a small zone extending about 40 to 50 inches beyond the nose of the tuyères. No further burning of the coke can take place outside of these small combustion zones; therefore the coke is shrinking or disappearing only within these rather small zones around the periphery of the furnace.

If dry air is saturated with carbon by introducing it into an incandescent fuel bed, a gas composed of about 66 per cent nitrogen and 34 per cent carbon monoxide is produced. This composition is the result of the fixed ratio of oxygen and nitrogen in dry air (264 parts oxygen to 1,000 parts nitrogen by volume). The small percentages of nitrogen in the center of the furnace indicate that oxygen combining with the carbon is derived from some other source than the blast, for example, metallic oxides in the charge. Such dilutions of nitrogen as those found show moreover that the main gas stream does not flow freely through the central area at the tuyère level.

Figure 3 is a diagram of the combustion zones in front of the tuyères. This is a cross section of the tuyère level. Before the gas samples were taken from the tuyères by Perrott and Kinney the general opinion was that combustion was occurring all across the hearth of the furnace. Actually there is a big inactive area in the center of the furnace. Figure 3 shows the length of the combustion zones as 40 inches on each side, which leaves an inactive zone 82 inches in the center of a 13-foot 6-inch hearth. Data from furnaces of varying hearth diameters indicate that the combustion zones are about the same size for a small furnace as for a large one. This means that the inactive zone at the tuyère level of a furnace with a hearth diameter of 25 feet represents a large portion of the total area. In spite of this condition hearth areas have been increased until the 600-ton furnace of 10 years ago now produces 1,000 tons per day. The larger furnaces have operated more smoothly, but the gain in production has not been in proportion to

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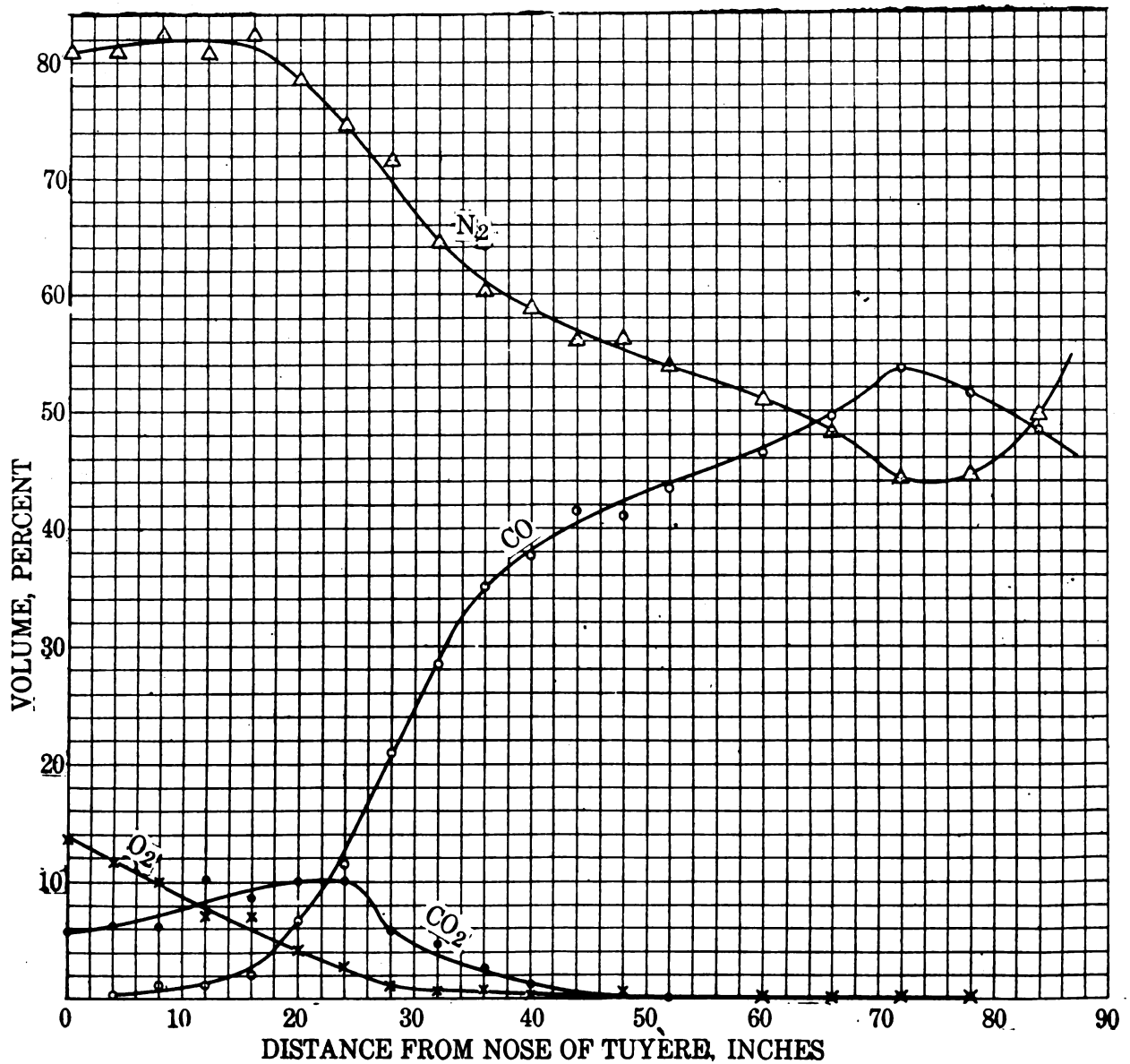

Figure 2.- Tuyère-gas analyses; average of results from 13 furnaces.

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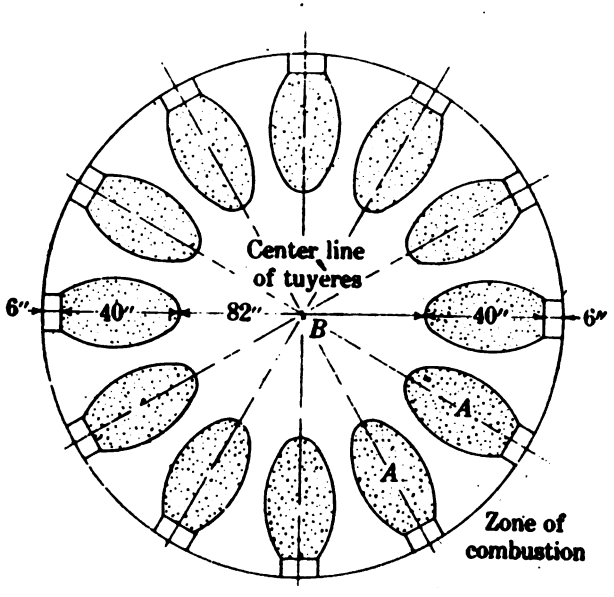

Figure 3.- Plan of tuyère plane, showing extent of penetration of combustion zone.

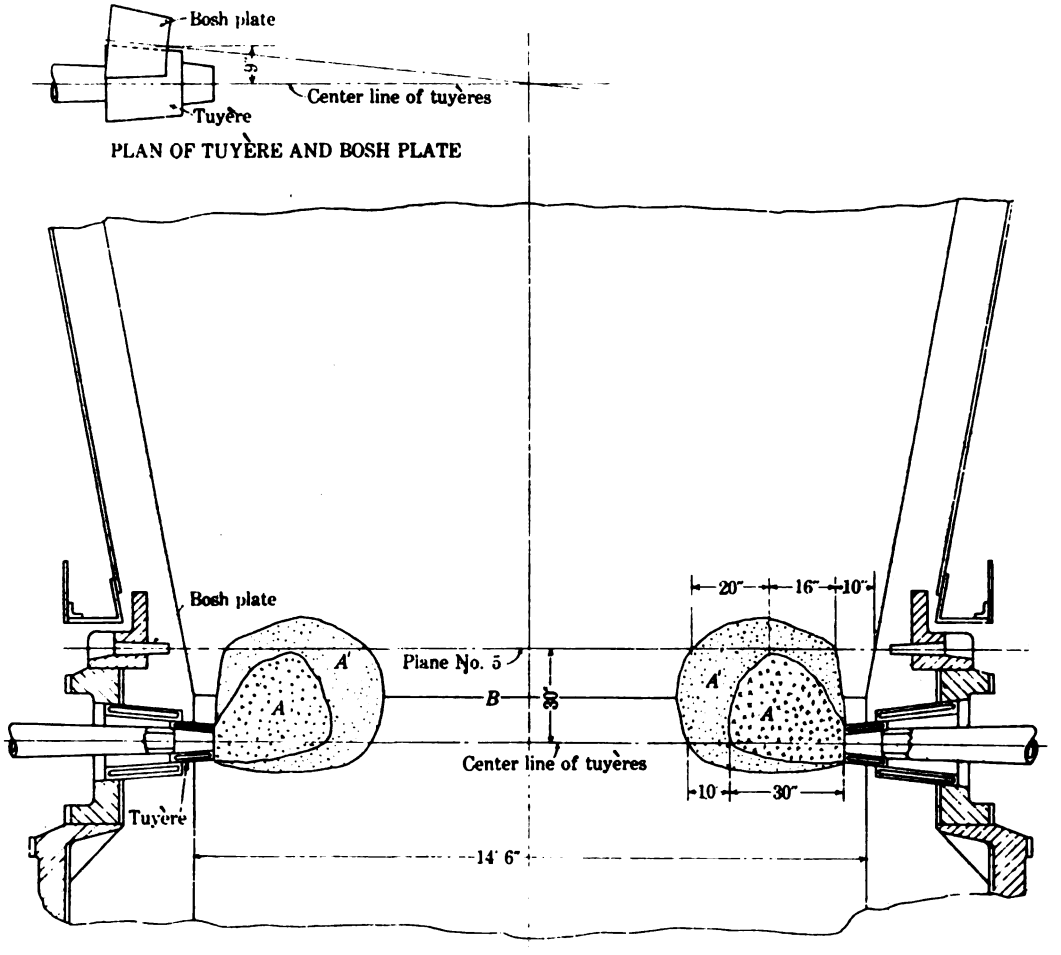

Figure 4.- Approximate size and shape of combustion zone.

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hearth areas and there has been no definite improvement in fuel consumption. As the hearth has been widened and the bosh deepened and lowered the mechanical settling of the stock has been aided. Heat losses have been lowered substantially in the 1,000-ton furnace. Some of the advantages of the large furnace from the standpoint of fuel economy apparently have been offset by certain other inherent disadvantages.

Figure 4 shows the approximate size and shape of the combustion zones according to Kinney.[4] The dotted areas lying on each side of the furnace represent the combustion zones in front of the tuyères. The smaller area designated by the letter A is one in which free oxygen exists. Area A represents a section in which carbon monoxide occurs in greater percentages; consequently, this zone is more strongly reducing.

Inactive Core at Tuyère Level

Several bits of evidence indicate that the central portion of a blast furnace at the tuyère level and probably at higher levels in the bosh is comparatively inactive. As previously stated, the gas in the central portion of the furnace at the tuyere level contains less nitrogen than the main gas stream generated in front of the tuyères, indicating that the gases do not flow readily through the central area; if they did, one would obtain a nitrogen content of about 60 per cent in place of as low as 44 per cent. (See fig. 2.)

The distribution of heat in the blast furnace depends largely upon convection. In and above the tuyère zone the temperature depends upon the amount of heat carried to a particular part of the furnace by the gas stream. A limited gas flow means comparatively low temperatures. Kinney found the center of the furnace to be about 800° C. colder than the tuyères.

In taking samples through the tuyères by means of a water-cooled tube it was observed that the sample tube could be pushed into the stock fairly easily for about 30 inches. At this point it was usually necessary to use a dolly to drive the tube farther in toward the center of the furnace. The stock was apparently held together more tightly in a plastic condition.

Localized Combustion at Tuyères and Flow of Stock

The coke is burned in a comparatively small area around the periphery of the furnace; therefore the stock settles faster in the area immediately above the combustion zone. The over-all result is a more rapid descent of stock along the periphery of the furnace than in the center of the furnace. Kinney[5] concluded from measurements of stock flow in the furnace (shown in fig. 1) that the stock near the walls was moving approximately one-third

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4. Kinney, S. P., Royster, P. H., and Joseph, T. L., Iron Blast-Furnace Reactions: Tech. Paper 391, Bureau of Mines, 1927, p. 35.
5. Kinney, S. P., The Blast-Furnace Stock Column: Tech. Paper 442, Bureau of Mines, 1929, p. 39.

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faster than the average rate of stock movement and that the center of the column was moving at a rate considerably lower than the average. This difference in rate of stock travel operates against a true countercurrent movement of solids and gases.

Factors Controlling Distribution of Gas

Uniform distribution of the gases in the blast furnace affords the greatest opportunity for the gases to give up their heat to the solid charge and for the maximum utilization of the reducing power of the gases. Uniform distribution of gas implies that the charge offers uniform resistance to gas flow; that is, the voids between the lumps of the charge in the center of the furnace and along the periphery must afford the same effective free area through which the gases may pass. This effective free area or interstitial space depends to a very large extent upon the size of solid particles occupying a given part of the furnace. In general, the resistance to gas flow varies inversely as the 1.2 power of the diameter of the particles; that is, pieces ½ inch in diameter will offer more than twice as much resistance to gas flow as pieces 1 inch in diameter. Figure 5 shows how rapidly the resistance to gas flow increases in the range of sizes from 8- to 14-mesh. Uniform gas distribution obviously requires uniform size distribution.

Size segregation

It is well known that in a pile of unsized material the large pieces roll to the outside. When one considers the enormous disparity in the size of the average Lake ores and of metallurgical coke and limestone, the difficulty of charging such materials without excessive size segregation becomes apparent at once. The ore particles range in size from dust to pieces several inches in diameter, while the limestone and the coke will range from 2 to 6 inches in diameter.

The raw materials are charged into a blast furnace by means of a bell and hopper, shown at the top of figure 1. The bell is usually 15 feet in diameter and the stock line 17 feet. This leaves a 2-foot clearance between the bell and the furnace wall. As the bell is lowered the charge slides off and arranges itself in layers as shown by the furnace model[6]. The dark layers which are thick at the wall and thin in the center are the iron ore. The lighter layers of coke are thin near the walls and thick in the center of the furnace. Such an arrangement is to be expected from the difference in the size of the ore and the coke. The small particles of ore tend to build up around the periphery, while the larger particles of coke tend to roll toward the center of the furnace.

Angle of Repose

In a series of tests with furnace models many observations were made on

6. Furnas, C. C., and Joseph, T. L., Stock Distribution and Gas-Solid Contact in the Blast Furnace: Tech. Paper 476, Bureau of Mines, 1930, p. 17.

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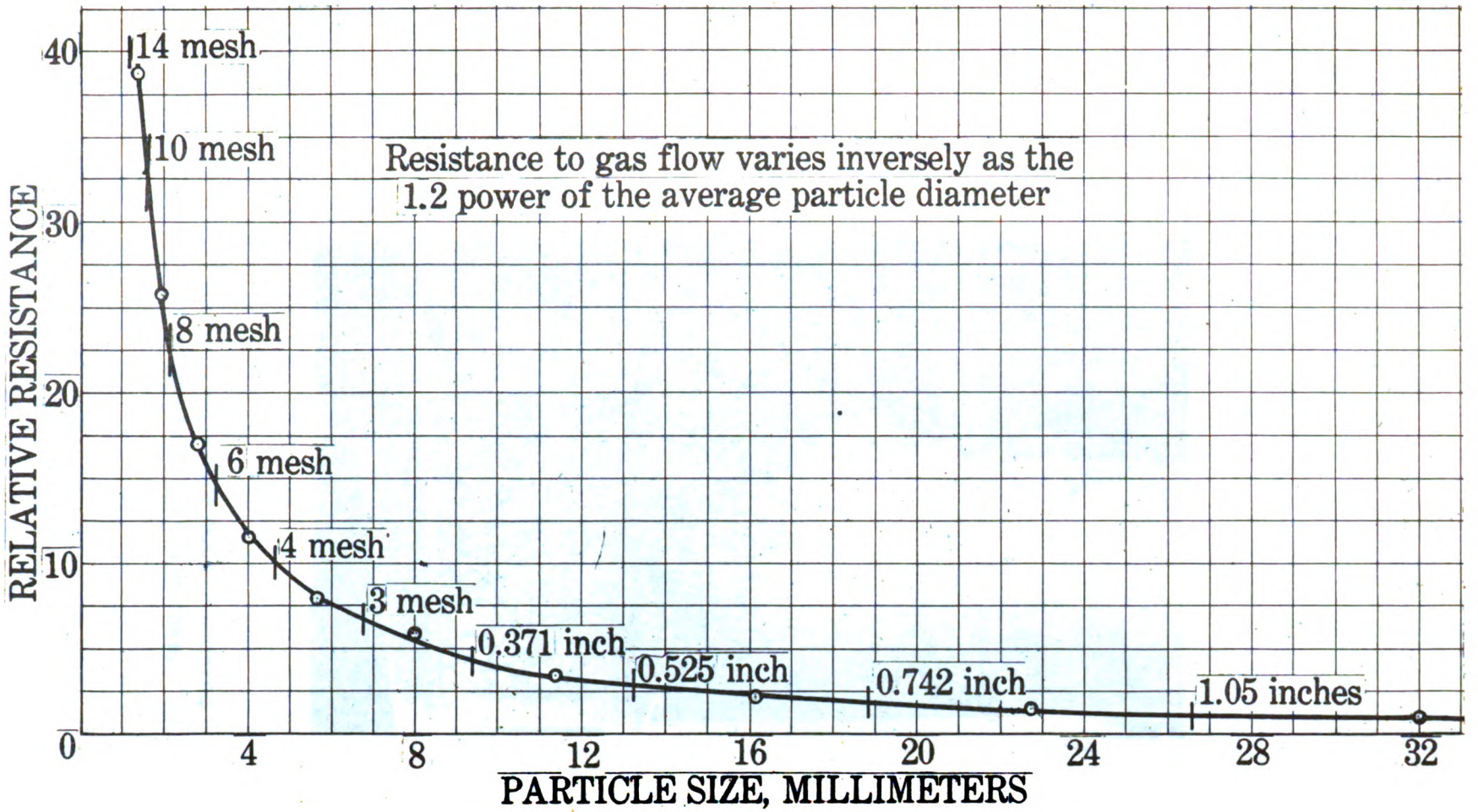

Figure 5.- Relation between particle size and resistance to flow of gases.

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Figure 6.- Furnace model, showing arrangement of ore and coke.

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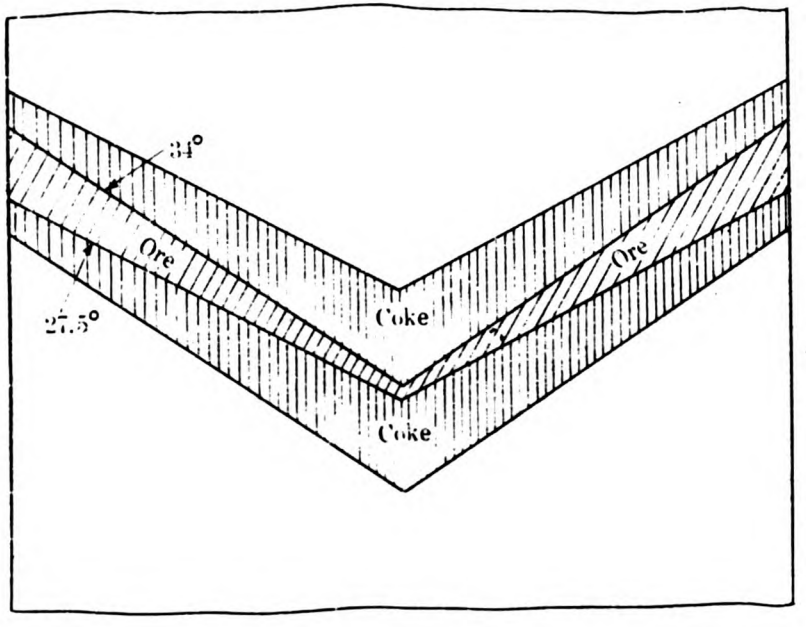

Figure 8.- Generalized diagram of cross-section of stock in the blast furnace.

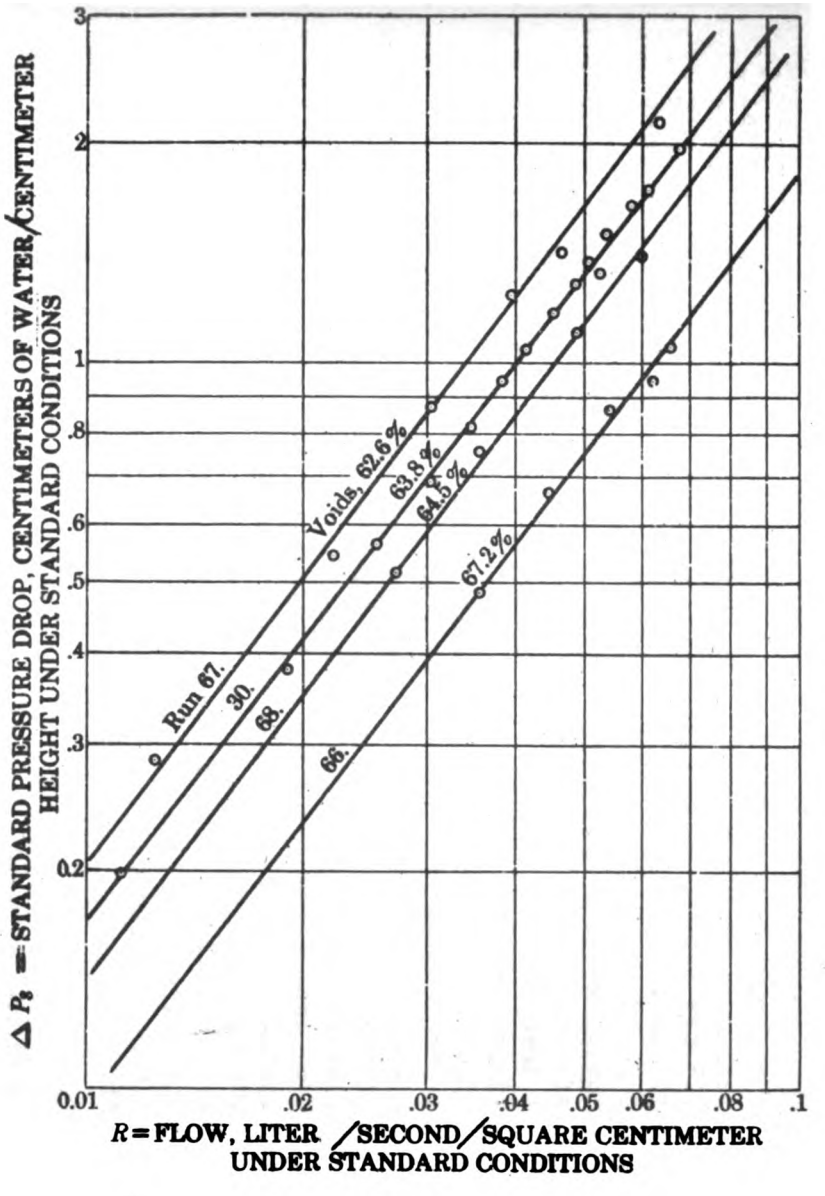

Figure 9.- Variation of unit pressure drop with packing of Cuyuna iron ore no. 1, 10- to 14-mesh.

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the angle of repose of the ore and of the coke after they had settled into place on the stock line. For the ore layers the average angle of repose was 34°, and for the coke layer the average angle of repose was 27.5°. This difference in the average angle of repose of ore and coke is an important factor in the causes of size segregation. Figure 8 is a generalized diagram[7] of the arrangement of the ore-coke layers. This sketch shows a larger ratio of ore to coke near the walls than in the center. If the ore particles are smaller than the coke, the average particle size will be smaller near the walls, and the resistance to gas flow will be greater. In a furnace with a 17-foot stock line the ore layer for normal charging is probably about 1 foot thicker at the walls than in the center; that is, if the layer of ore is only 1 foot thick at the wall it would be approximately zero thickness at the center and the ore-coke ratio would be zero at this point. The corresponding coke layer might be 0.5 foot thick at the wall and 1.5 feet at the center. Suppose the size of the charge were doubled: The ore layer would then be 1.5 feet thick at the wall and 0.5 foot thick at the center. The corresponding coke layer would be 1.5 feet thick at the wall and 2.5 feet at the center. Thus it can be seen that the size of the charge affects the ratio of ore to coke in various sections of the furnace. A variation in the ratio of ore to coke has a pronounced effect upon the relative resistance of the charge to gas flow. It is more important than segregation of large lumps within the ore layer.

Summary of Causes and Control of Size Segregation

Factors which decrease and increase average particle size in center of furnace

1. Size segregation in a furnace is due to: (a) Greater ore-coke ratio at the center than at the wall caused by a greater angle of repose of the ore, and (b) the large particles of ore tending to roll toward the center.

2. The average size of particles at the center may be decreased by decreasing the time of depositing materials on the bed. This may be done by: (a) Keeping the stock line close to the bed; (b) increasing the bell angle; (c) increasing speed and distance of bell drop; and (d) increasing bell clearance.

3. The average size of particle at the center is increased by: (a) Reversed filling--coke on the big bell first; (b) mixing--alternating skips of ore and coke; (c) decreasing size of ore charge; and (d) decreasing bell clearance.

4. Unit charging--charging ore and coke separately--seems to have little effect.

5. About 12 per cent of the extra water in the ore is undesirable for charging. Greater or less amounts of water than this have little effect on the charging characteristics.

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7 See footnote 6, p. 27.

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Uniformity of Size

Homogeneity in size is an important factor in blast-furnace materials. A large variation in the size from one ore lump to another and from ore lumps to coke lumps will inevitably lead to size segregation and to nonuniformity in the flow of gas. Some particles of the stock will be more or less shielded from the gas stream, while others will be in a strong current of gas. The sheltered particles will reach the lower part of the furnace cold and unreduced. Heat transfer from gases to solids and deoxidation of iron ore, both of which depend upon gas-solid contact, are not carried out efficiently if one part of the furnace gets excess gas and the other part a deficiency of gas. The operator can change the gas distribution of his furnace within certain limits by changing his method of filling. The problem of gas distribution can be greatly simplified by the use of a charge having greater homogeneity in size. As the particles in a charge approach the same size there is little segregation of large and small pieces, and resistance to gas flow approaches uniformity.

Sizing of Ore

Prompted by the general suggestion of the Bureau of Mines that uniform particle size in each layer should be beneficial, the Columbia Steel Co., Ironton, Utah, now a part of the United States Steel Corporation, is separating its ore into three sizes and charging each size separately. Kinney[8] has reported that in foundry practice sizing the ore saved about 500 pounds of coke per ton and increased production 110 tons per day. On basic pig iron the coke saving amounted to about 440 pounds per ton, and production was increased about 82 tons per day. More recently investigations into the possibility of crushing and sizing Alabama ores have led to promising results.

Sizing of iron ore and charging the sizes separately would probably not be advisable if more than one half the ore were smaller than 0.5-inch. Lake ores, as a whole, contain too large a proportion of fines to be charged successfully in sized portions. One company is now shipping fine sizes separately for sintering at the furnaces. As the concentration of iron ore develops and greater attention is paid to recovery of fine ore particles sintering or agglomeration will increase.

Sizing of Coke

Some plants have adopted the practice of sizing their coke. The results have not been as pronounced as those from sizing ore. One important effect of sizing coke is that in the sizing operation there is a tendency to segregate weaker pieces of coke into the small sizes.

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8 Kinney, S. P., Effect of Sized Ore on Blast-Furnace Operation: Tech. Paper 459, Bureau of Mines, 1930, p. 17.

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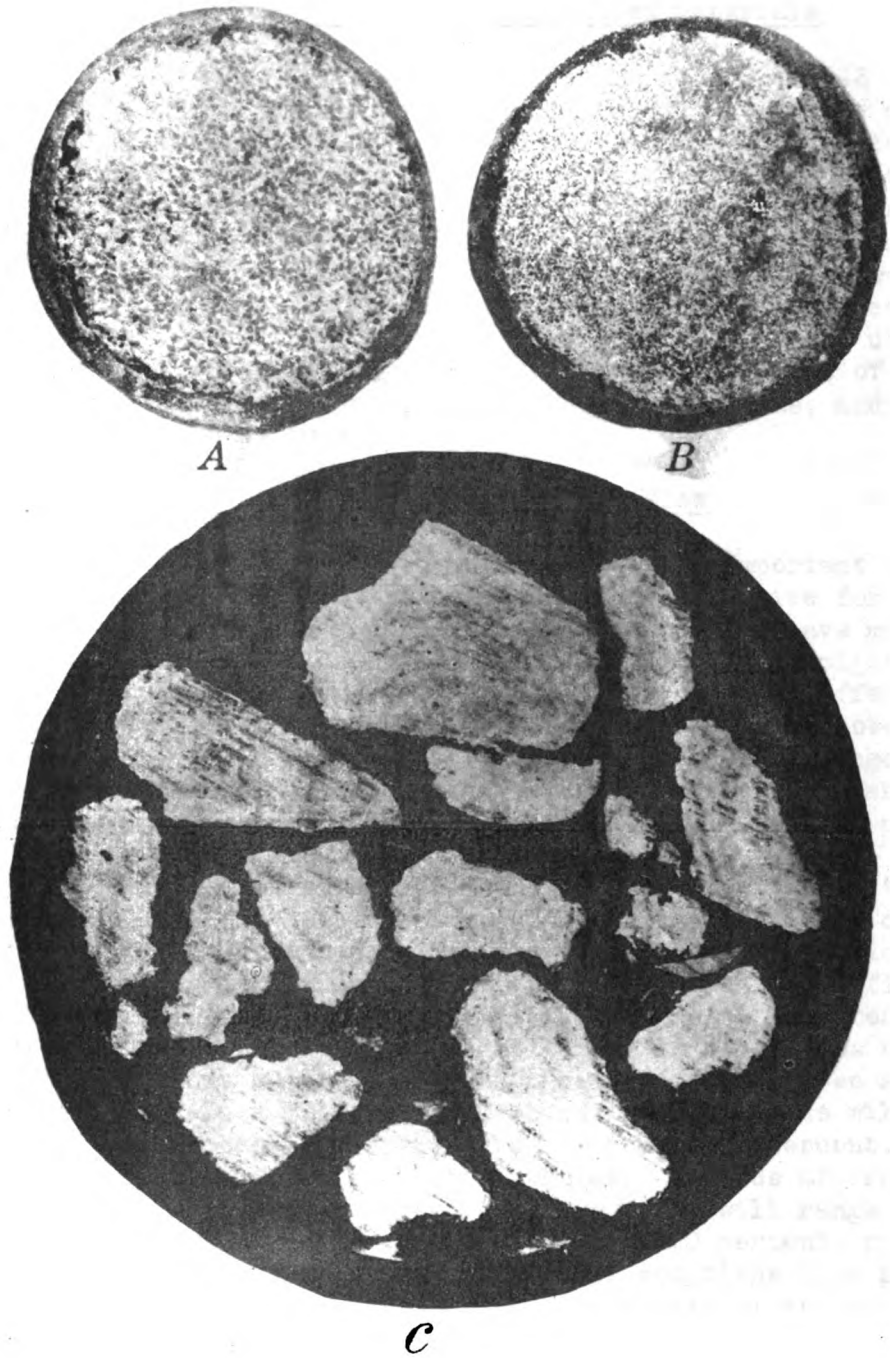

Figure 7.- Cross-sections of a bed of 1.05- to 0.742-inch limestone and beds of fine iron ore: A, 14- to 20-mesh Cuyuna ore; B, 28- to 35-mesh Cuyuna ore; C, 1.050- to 0.742-inch limestone.

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Voids in Beds of Sized and Unsized Materials

The voids in beds of unsized ore will range from 33 to 43 per cent of the total volume. In a bed of particles all approximating the same size the voids will range from 50 to 60 percent under comparable conditions of packing for both types of beds. The charge used in the furnace of the Columbia Steel Co. was fairly coarse, partly sized, and contained 47.5 percent voids. The charge, including coke, ore, limestone, and miscellaneous materials, for a furnace using Lake ores contained 33.2 percent voids. Figure 7, which shows cross-sections of a bed of 1.05-to 0.742-inch limestone and of beds of fine iron ore, may enable the reader to visualize the vast difference in the size and number of passageways for gas flow through beds of broken solids. The dark areas are the voids in the bed of limestone, and the light areas represent the voids in the beds of ore.

Effective Area for Gas Flow

The increase in voids in sized material is more important than it might appear to be because all of the void space is not effective for gas flow. Gases do not move around sharp corners and consequently leave many dead spaces in the voids. A bed of typical blast-furnace stock might have 33 percent voids, but only 10 percent of the total area might be effective for gas flow. This means that the gases in the blast furnace move faster than one might expect on the basis of the total voids, also that a change in uniformity of size or absolute size, which changes the effective free area by 1 percent, is really a change of 1 part in 10 and not a change of 1 part in 33.

Furnas[9] found the resistance of a bed of broken solids to the flow of gas varied markedly when the percentage of voids was changed a comparatively small amount by packing the bed. Figure 9 shows that a reduction from 37.2 to 32.6 percent voids more than doubled the resistance to gas flow. This large change in resistance was due to a large change in the area effective for gas flow. In a loosely packed condition a pile of spheres of uniform size will contain about 50 percent voids and an effective free area for gas flow of 20 percent. In a closely packed condition the voids will be about 25 percent and the probably effective free area about 9 percent. These figures are independent of the size of the spheres. In beds of iron-ore particles of approximately the same screen size the voids will range from 40 to 60 percent and the effective free area from 10 to 20 percent, provided the particles are allowed to drop singly into their positions in a bed and no bridging or packing occurs except that characteristic of the material. The effective free area in a blast-furnace charge, representative of Lake ore practice, was 8.15 percent, and the voids were 32 percent.

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9 Furnas, C. C., Flow of Gases Through Beds of Broken Solids: Bull. 307, Bureau of Mines, 1929, p.32.

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Conditions Inside Blast Furnace

Variations in temperature, gas velocity, and composition of gas

The Bureau of Mines has investigated the interior conditions of blast furnaces by taking samples of gas for analysis, by temperature readings, and by gas-velocity readings. These observations by Kinney[10] tell a coherent story as to the nonuniformity of the furnace from the edge to center at elevations between the top of the bosh and the stock line. Figures 10, 11, and 12 show the carbon dioxide content, the temperatures, and gas velocities, respectively, at various planes as found by Kinney in a 700-ton furnace. The carbon dioxide shows about a threefold variation, the temperature almost a fivefold variation, and the velocity of the gas about a sixfold variation across a plane near the stock line. High gas velocity is accompanied by high temperatures and comparatively low percentages of carbon dioxide. This nonuniformity in plane 1 in the cylindrical section of the top is due primarily to size segregation. The variation in gas velocity from about 80 feet per second along the wall to 480 feet per second in the center of the furnace indicates that the average sized particle was about 0.5 inch along the wall and 4.5 inches in the center of the furnace. There was very little, if any, ore in the center of the furnace.

Effect of heat capacity of charge on heat transfer

The temperature at any given position in the stock column of a blast furnace depends in general upon the heat carried to that part of the furnace by the gases and upon the heat capacity of the charge. Where the ore layers are thicker the temperature is low because of the small gas flow, which means small heat input, and because the stock has greater heat capacity due to the larger weight per unit volume. A cubic foot of coke weighs about 30 pounds, whereas a cubic foot of ore weighs about 150 pounds. The specific heat of coke is about 0.25, or very near the specific heat of ore, 0.266. A cubic foot of ore will therefore have about five times the heat capacity of a cubic foot of coke.

Nonuniformity of gas flow, temperature, and gas composition is not so bad as is pictured by figures 10, 11, and 12 because the greatest discrepancies lie where the area per width of annular ring is small. A ring 1 foot wide at the periphery of a 17-foot stock line has as much area as a ring 4 feet wide extending from the center.

Explorations of conditions in seven industrial furnaces have shown various degrees of nonuniformity in gas flow, temperature, and gas composition. The furnace operated at Ironton, Utah, on sized ores was the most uniform furnace investigated. Splitting the ore into three sizes (medium, fine, and coarse) and charging each size separately have resulted in

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10 See footnote 5, pp. 101-104.

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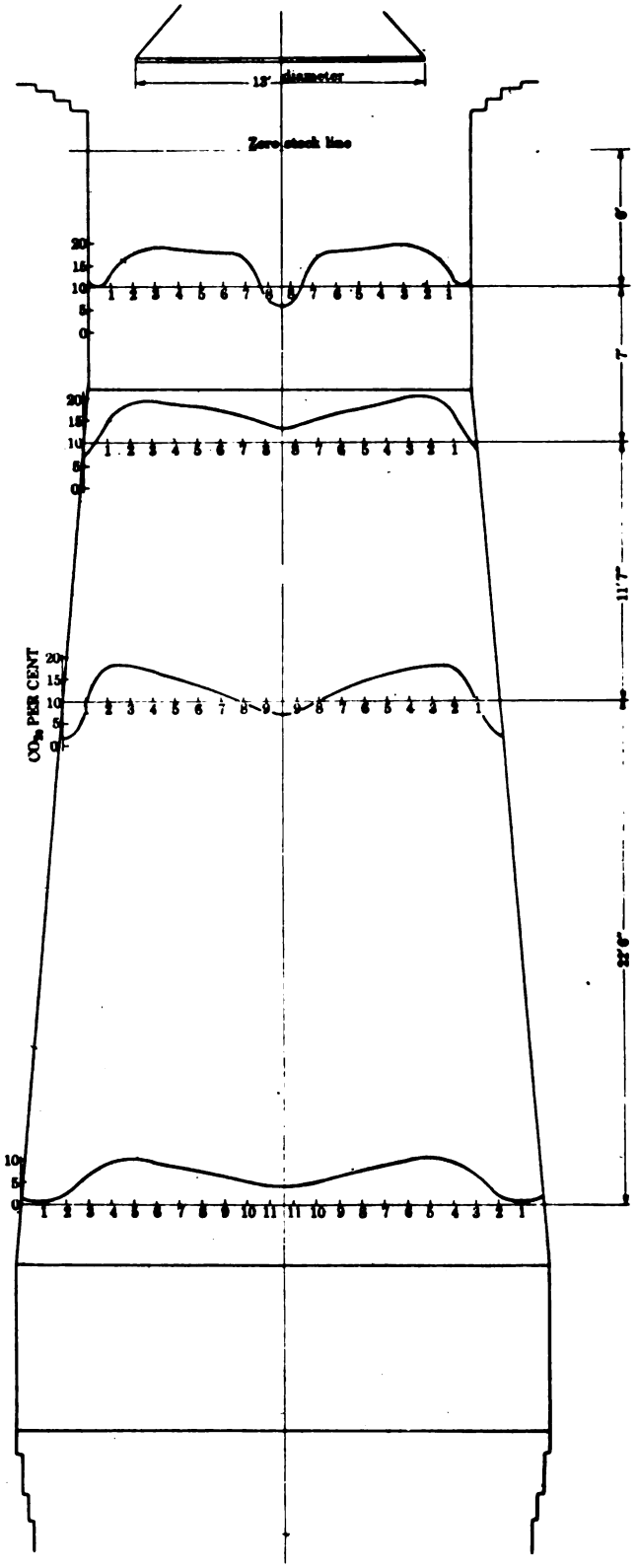

Figure 10.- Carbon dioxide content of gases at various planes.

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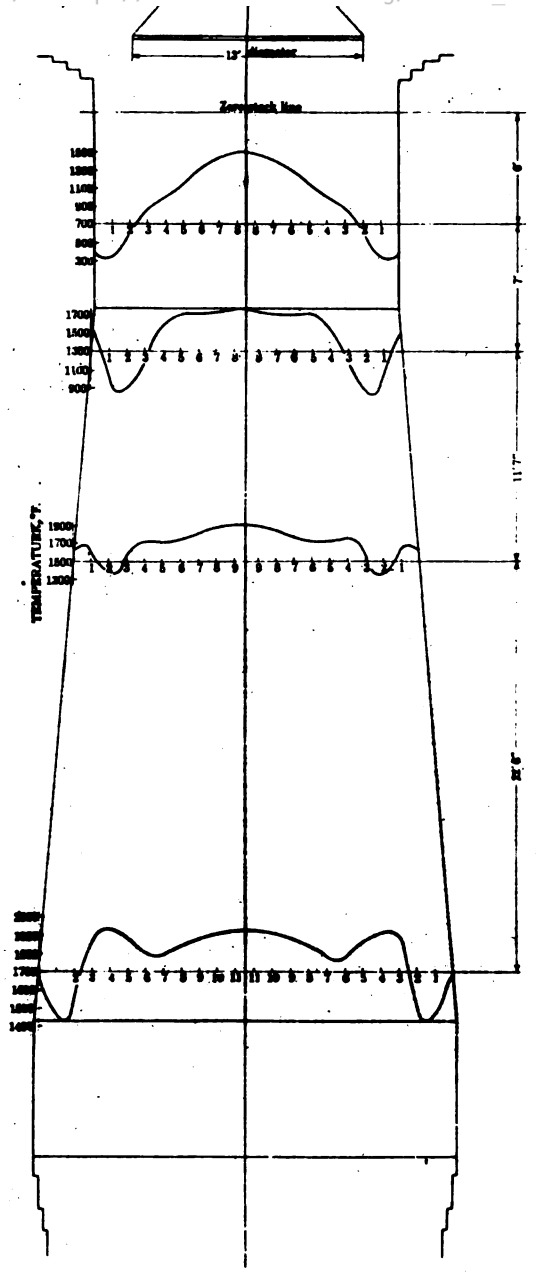

Figure 11.- Temperature at various planes, °F.

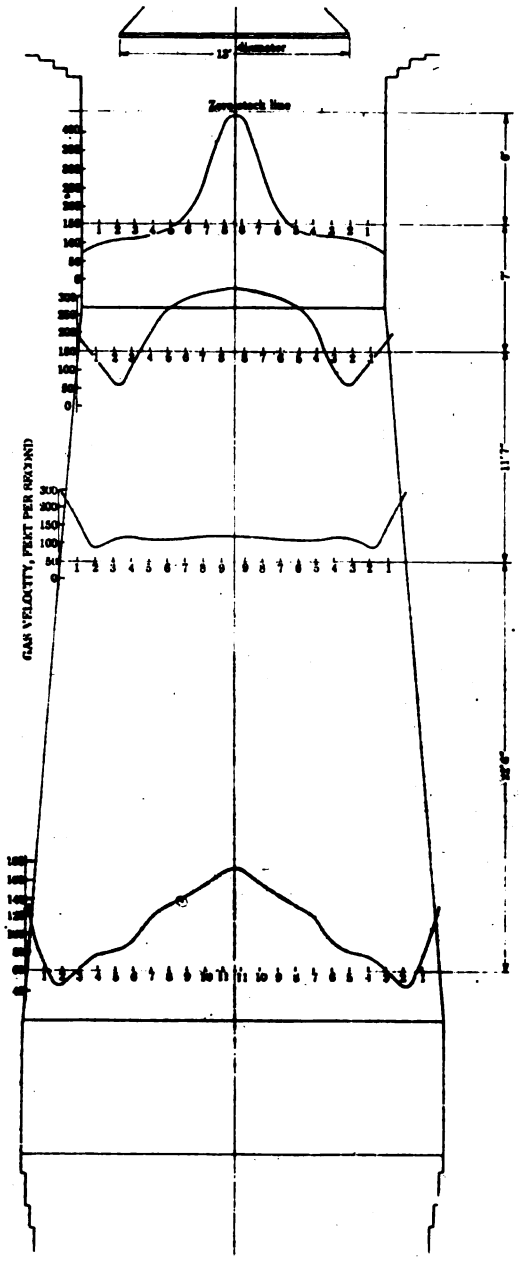

Figure 12.- Gas velocity at various planes.

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minimizing size segregation at the stock line.

Effect of Furnace Lines on Gas Distribution

In general, the course of the gas in a blast furnace above the fusion zone is controlled by the size distribution of the charge. However, the batter of the furnace, which may vary from 3/4 to 1-3/16 inches in 12 inches, has a decided effect upon the amount of gas which moves along the walls of the furnace. This is shown in figures 10, 11, and 12. Temperature observations, gas-velocity readings, and the carbon dioxide in the gas show very little, if any, wall effect along plane 1 located in the cylindrical section of the furnace. There is a pronounced wall effect in the lower three planes, where the wall has an inward slope or batter of 1 inch in 12. Kinney explored two furnaces which were comparatively open along the walls and dense in the center. These furnaces had the same bell clearance and were charged the same way as the furnace shown in figures 10, 11, and 12, which had an open center and a relatively dense periphery. The only observable differences were that the two furnaces with open walls had 1/16 inch greater batter on the sidewall, the hearths were 2-1/2 feet wide, they were blown 25 to 30 percent faster, and they had no flue dust in the charge, whereas the third furnace had about 300 pounds of flue dust in the burden. Bureau of Mines observations show that it is very difficult to predict the action of a furnace. Surveys, such as those made by Kinney, show the existing conditions for a given furnace and afford a basis for correcting undesirable features.

Within the past 10 years hearth diameters have been increased from 16 or 18 feet to as much as 28 feet. It is only within the last 2 or 3 years that stock-line diameters have been increased beyond 17 feet. This gradual widening of the top has led to steeper batters. The present tendency is to increase the top diameters and to be more conservative in increasing hearth diameters. Excessive production of flue dust in furnaces with narrow tops in proportion to hearth diameter and amount of wind blown have been responsible in a large measure for the development toward wider tops. As the top diameters are increased and brought into a more consistent relation with dimensions in the bottom of the furnace batters of 0.75 to 0.8 inch per foot will become more common.

The discovery by the Bureau of Mines of an unrealized degree of nonuniformity in furnaces has focused attention upon ways and means of obtaining more uniform conditions of temperature, of gas velocity, and of gas composition from the periphery to the center of the furnace. However, with such a disparity in particle size of Lake ores and metallurgical coke, any approach to uniform gas flow will be difficult. Segregation of fine sizes at the mines, the increased use of sinter, and sizing of raw materials will be a forward step toward more uniform conditions inside the blast furnace. With coarse ores, such as the Alabama ores, sized charges can be used without the problem of extensive sintering. Experience with wider tops, greater bell clearance, and less batter of the inwall probably will lead to better relationship between size of raw materials, methods of filling, and furnace batter.

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Effect of Gas Distribution Upon Reduction

If the gas is distributed uniformly through the stock, the iron ore will be deoxidized at higher levels in the furnace. A charge which contains fine ore will usually result in excess ore to coke in some part of the furnace. The inevitable result is restricted gas flow where there is greatest need for heat and reducing power. Fine ore offers a large amount of potential surface for contact with carbon monoxide. However, it is very difficult to take advantage of this enormous surface because it is mechanically impossible to move fine ore directly countercurrent to large volumes of gas.

Figure 13 shows data obtained by Kinney[11] on the percentage of total oxygen in the ore which had been removed by the time the ore reached various levels of three furnaces. In the Ironton furnace 96.6 percent of the oxygen was removed by the time the ore reached a level about 42 feet below the stock line (near the top of the bosh). At about the same level only 24.4 percent of the oxygen had been removed from the ore in furnace No. 4. Such a striking difference in two furnaces raises the question as to why most of the oxygen was removed from the ore in the upper section of the Ironton furnace and in the bottom section of furnace No. 4. A general reply to this question would be that in furnace No. 4 there was less contact between the rising current of carbon monoxide, the agent for removing oxygen, and the iron ore. This comparatively poor contact in furnace No. 4 was due to nonuniformity in gas flow caused by size segregation. There was a pronounced tendency for the gas to channel up through the center of the furnace where there was comparatively little ore.

Uniformity of Size and Absolute Size

The more uniform gas flow in the Ironton furnace was not due to a coarser burden because the average particle size was 1.41 inches for the Ironton furnace on these sizes of ore and 1.61 inches for furnace No. 4. A study of the size of ore, coke, limestone, and miscellaneous materials used in these two furnaces shows that the Ironton materials were more uniform in size. Kinney[12] found that 1 cubic foot of Ironton furnace stock contained 47.8 percent voids and weighed 63.3 pounds and that 1 cubic foot of stock from furnace No. 4 contained 33.2 percent voids and weighed 95.5 pounds. These values were obtained by thoroughly mixing a ton of all the material proportioned by weight.

Uniform Gas Flow and Blast Pressure

The blast-furnace charge settles under the force of gravity. If the over-all resistance of the blast-furnace stock column is too great, high pressure and wall friction exceed the force of gravity and the furnace hangs. In order to meet production demands, operators must work out methods of filling which will allow them to blow large volumes of air without building up

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11 Kinney, S. P., Effect of Sized Ore on Blast-Furnace Operation: Tech. Paper 459, Bureau of Mines, 1930, p. 84.

12 See footnote 11, p. 28.

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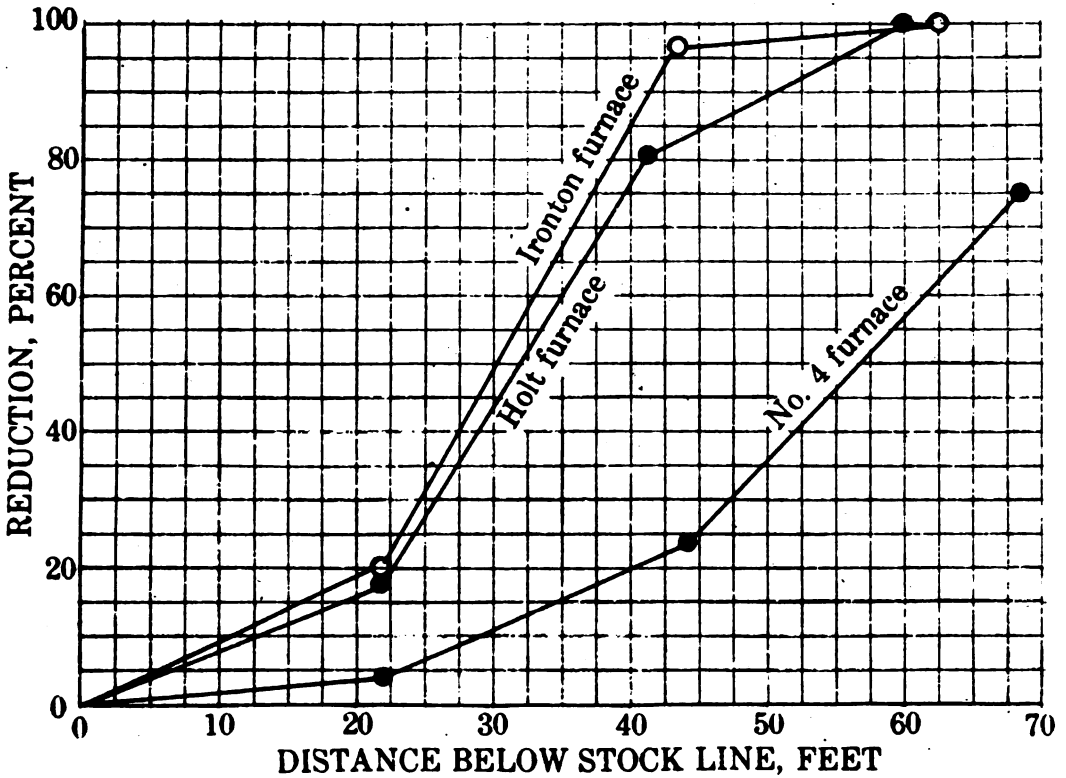

Figure 13.- Reduction at various depths below stock line.

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pressures which counterbalance the force of gravity. With fine Lake ores it seems that there must be a relatively porous area in some portion of the charge which will act as a relief valve for large volumes of gas and thus prevent high pressure.

If we consider two cases, one a uniform bed in which all sections offer the same resistance to gas flow and another bed in which 90 percent of the cross-section is uniform, with 10 percent acting as a chimney, we find that the small open section, although it is only 10 percent of the area, has a pronounced effect upon the pressure drop through the bed. For example, if the average particle size in the chimney which represents 10 percent of the total area is 6 inches and the average particle size in the remaining 90 percent of the bed is 1/2 inch, the over-all resistance is cut down 25 percent by the presence of the chimney. Such a decrease in pressure would make a substantial difference in wind blown and the daily tonnage that might be produced. From a purely mechanical point of view of getting material through the furnace the operator is able to meet tonnage demands by sacrificing gas distribution. Unless more uniform size distribution of blast-furnace stock is accompanied by coarsening of the burden, blast-furnace pressures are apt to be higher. Sizing of iron ore at Ironton, Utah, was accompanied by slightly higher blast pressures.

Advantage of Deoxidizing Iron Ore in Top of Blast Furnace

The amount of coke required to produce 1 ton of pig iron is determined by hearth-heat requirements. In general, hearth-heat requirements for a particular furnace depend upon the silicon and sulphur specifications for the pig iron. Carbon in pig iron is fixed within narrow limits by the nature of the process. Phosphorus is governed entirely by the phosphorus in the charge; and manganese, although dependent somewhat upon smelting losses, is likewise regulated by varying the manganese in the charge. From cast to cast and day to day operators keep a close watch over the silicon and sulphur in the metal. High-sulphur and, in general, low-silicon iron, which means off-grade iron, follows closely upon the heels of low hearth temperatures, which implies cold tuyeres, cold slag, and cold iron.

The advantages of deoxidizing iron ore in the top of the blast furnace are not apparent until secondary reactions are considered. Carbon monoxide generated at the tuyeres of a blast furnace removes oxygen from the ore according to the following reaction:

$$Fe_2O_3 + 3\,CO \quad 2Fe \quad 3CO_2.$$

If this reaction proceeds at elevations in the furnace where the temperature does not exceed 1,000° C., the greater part of the carbon dioxide so formed leaves the top of the furnace. If the reaction proceeds at temperatures exceeding 1,000° C., a so-called secondary reaction takes place as follows:

$$CO_2 \quad C \text{ (in coke)} \quad 2\,CO.$$

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In addition to absorbing heat this reaction uses up coke carbon needed to attain temperatures at the tuyeres necessary in controlling the silicon and the sulphur in the metal. The more intimate the gas-solid contact in the upper part of the furnace the more nearly will conditions approach those in the ideal furnace advocated by Grüner.[13] According to Grüner's ideal all reduction should take place by carbon monoxide, and the resulting carbon dioxide should leave the furnace without reacting with the carbon in the coke. That this is the correct principle by which the maximum heat may be generated from a given weight of fuel may be more fully realized by recalling that 1 pound of carbon burned to carbon monoxide develops 4,375 B. t. u., whereas 1 pound of carbon burned to carbon dioxide develops 14,750 B. t. u. or more than three times as much.

Direct reduction

Direct reduction with solid carbon is alleged to occur according to the equation,

$$FeO + C = Fe + CO.$$

It is debatable whether this is not the net result of the reactions,

$$FeO + CO = Fe + CO_2,$$

and

$$CO_2 + C = 2\ CO.$$

This is an academic question, as the effect is the same in both cases; that is, the coke carbon needed to generate heat at the tuyères is used above the tuyeres by a heat absorbing reaction.

Percent carbon gasified at the tuyères

As a result of premature combustion of the coke by oxygen from the ore or limestone, substantial amounts of carbon are gasified above the tuyères. Data, compiled by the writer[14] and covering 55 American furnaces, showed that an average of 384 pounds of carbon per ton of pig iron was gasified above the tuyères. Evans, Reeve, and Vernon[15] examined data from 145 furnaces and found that in the maximum number of furnaces 350 pounds of carbon were gasified above the tuyères. In general, 20 to 25 percent of the carbon is gasified above the tuyères.

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13 Grüner, M. L., Blast-Furnace Phenomena: Translation by L. D. B. Gordon, Henry Cary Baird Co., Philadelphia, Pa., 1874, p. 28. Johnson, J. E., Jr., Principles, Operation, and Products of the Blast Furnace: New York, 1918, pp. 1, 75, 95. Richards, Joseph W., Metallurgical Calculations: New York, 1918, p. 274.

14 Joseph, T. L., Behavior of Coke in the Blast Furnace: A Review: Yearbook, Am. Iron and Steel Institute, 1927, p. 436.

15 Evans, E. C., Reeve, L., and Vernon, M. A., Blast-Furnace Data and Their Correlation, Part II: Paper presented at May, 1931 meeting, Iron and Steel Inst., p. 4.

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Fine materials make it difficult to approach Grüner's ideal furnace

This mechanical movement of fine ore countercurrent to large volumes of gas usually requires a sacrifice of gas-solid contact. Decidedly bad practice results from furnaces which hang and slip due almost entirely to high resistance to gas flow offered by the column of stock. If the operator is forced to use fine ore, he charges his furnace so that he can meet tonnage requirements and accepts whatever gas distribution may result from his method of charging. With an average grade of Lake ore (51.5 percent Fe and 8.5 percent SiO_2) and average coke he can still produce a ton of iron with a fair consumption of coke (1,900 pounds per ton of coke) by carrying high blast temperatures which assist very materially in maintaining the temperature at the tuyeres of the slag and of the metal. It should be borne in mind, however, that he is able to show a fair consumption of fuel in spite of not because of limited reduction in the top of the furnace.

Raw Materials

Fuels

Charcoal was the predominant blast-furnace fuel until 1838, when it was found that anthracite could also be used. The production of anthracite pig iron increased steadily, and in 1885 its tonnage exceeded that of charcoal iron. In 1874, 680 American furnaces were operated; 226 furnaces used anthracite and produced nearly 50 percent of the total tonnage. The tonnage of pig iron made with coke exceeded that produced with charcoal in 1869, and in 1875 coke surpassed anthracite as blast-furnace fuel. Coal is still used in Scotland to produce comparatively small tonnages of pig iron. The use of charcoal is declining. Coke has become the universal blast-furnace fuel.

Coke

Coke, which is an artificial product made by distilling most of the volatile matter from bituminous coal, is the ideal blast-furnace fuel because it can be produced in large porous pieces which are able to withstand the mechanical action of handling before charging and to withstand the abrasive action inside the furnace. Metallurgical coke of good quality undergoes a small amount of size degradation either before or after charging it into the furnace. Investigations of coke, which have furnished information as to its ability to retain its size and shape from the coke-oven wharf to the tuyeres of a blast furnace, have been the most fruitful in determining coke quality. The significance of the physical properties of coke is more readily appreciated if it is borne in mind that the blast-furnace process involves the countermovement of solids and gases. Coke, which has a low bulk density inside the furnace, offers the greatest aid in producing a column of ore, limestone, and coke some 70 feet high through which large volumes of gases may be moved uniformly and at comparatively low pressures. Low bulk density in the furnace implies low ash content, uniformly large pieces with no breeze or small sizes to fill the voids, and maximum porosity without sacrificing resistance to size degradation either by abrasion or breakage in handling.

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The primary function of coke is to produce high temperatures in the tuyère zones as well as to produce total heat units. At present, there is no positive correlation between coke properties and attainable temperatures upon combusion. Mott and Wheeler,[16] after an extensive study of coke properties, concluded:

1. Since the rate of combusion of coke at the tuyères depends upon the rate of supply of air and since this, in turn, depends upon the resistance of the charge to the passage of gasses, the presence of much coke breeze in the furnace will restrict its rate of driving.

(The foregoing assumes constant pressure blowing.)

2. The hearth temperature will be reduced by the presence of small coke.

3. A satisfactory hearth temperature can be most economically maintained with an "unreactive" coke containing but little breeze.

4. The size of a coke and its hardness affect the hearth conditions more than does specific reactivity.

The emphasis in these conclusions has been rightly placed upon physical characteristics rather than upon combustibility which has been widely and loosely discussed in the literature on coke quality.

Sulphur

From 85 to 95 percent of the sulphur entering the blast furnace is charged with the coke. It is now known rather generally that metal will absorb sulphur when heated in the presence of coke. Sponge iron, produced in a blast furnace or in other types of reducing furnaces, will absorb sulphur from the fuel. Kinney found that metal removed from a blast furnace 27 inches above the tuyères and 19 feet 3 inches above the tuyères contained 0.179 and 0.07 percent sulphur, respectively. Absorption of sulphur from the coke apparently continues from the time the metal is formed until it reaches the tuyères. If the coke contains 1 percent sulphur or under, there is no great difficulty in reducing the sulphur in the pig iron to less than 0.05 percent with normal amounts of slag. However, when the sulphur content of the coke exceeds 1 percent it is usually necessary to modify the practice to handle the sulphur successfully.

Difficulties with basic slags

Operators usually prefer to use higher slag volumes rather than smaller amounts of hotter and more basic slag to eliminate sulphur because basic slags tend toward irregular operation. The writer believes that much of this trouble is due to the tendency of limestone undergoing calcination to form a

16 Mott, R. A., and Wheeler, R. V., Coke for Blast Furnaces: Tech. Rept.1, Iron and Steel Industrial Research Council, Colliery Guardian Co. (Ltd.), London, 1930, p. 140.

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scaffold near the zone of fusion. It requires about 43,000 calories to calcine a formula weight of limestone. Such a heat requirement has a very decided effect in lowering temperatures in a region which derives its heat from the small heat capacity of gases. Scaffolds near the zone of fusion are the result of a portion of the stock remaining at sintering temperatures until permeability to gas flow is lost.

If only siliceous ores are available, the slag volume will be high, and the penalty for eliminating sulphur will be smaller. Operators, who are fortunate enough to have coke containing 0.6 percent sulphur, can meet sulphur specifications in the metal with 650 pounds of slag. With such a sulphur content and with high-grade ore it is not unreasonable to expect a fuel consumption of 1,500 pounds of coke per ton of metal. This quantity of coke would introduce 9 pounds of sulphur. If 1-1/2 pounds more are brought in with the ore and limestone, a total of 10-1/2 pounds of sulphur per ton of pig iron would be charged. A ton of metal will contain about 1 pound of sulphur, which leaves 9-1/2 pounds of sulphur to be eliminated in 600 pounds of slag, carrying about 1.6 percent sulphur.

The less-fortunate operator who is forced to use coke containing 1.2 percent sulphur will probably consume about 2,000 pounds of coke, which will mean a total of about 25-1/2 pounds of sulphur, including 1-1/2 pounds from the ore and limestone. Deducting 1 pound, carried off in the metal, leaves 24-1/2 pounds to be eliminated in the slag. Operators usually prefer 1,200 to 1,400 pounds of slag to eliminate this quantity of sulphur. Assuming that the operator with high-sulphur coke is forced to use siliceous ores or gravel to build up his slag volume to handle sulphur, the writer[17] has estimated that each additional 0.1 percent sulphur will add 14 to 20 cents to the cost of producing 1 ton of pig iron if coke costs $4 per ton. Such figures will not apply in all cases, but they show the importance of low-sulphur coke in an industry based upon large output and small profits per ton.

Coke ash

Coal used in the production of metallurgical coke should be low in ash as well as in sulphur. As the ash in coke increases the amount of fixed carbon and the calorific value decrease. Sweetser[18] has reported that an increase of 1 percent in coal ash, which corresponds to an increase of 1.45 percent in the coke ash, will add about 30 cents to the cost of pig iron if coke costs $6.50 per ton. Kinney[19] studied the effect of coke ash on the operation of a Southern foundry furnace over a period of 10 months during which the ash ranged from 12 to 24 percent. The following shows the distribution of additional costs due to an increase of 1 percent ash in the coke on the basis of $3.50 per ton for coke, $1.50 per ton for limestone, and $2.25 for costs above raw materials, which increase directly as the tonnage decreases.

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17 Joseph, T. L., Effect of Sulphur on the Blast-Furnace Process: Trans. Am. Inst. Min. and Met. Eng., vol. 71, 1925, p. 463

18 Sweetser, R. H., Clean Coal; How to Get It: Iron Trade Review, vol. 76, No. 23, 1925, p. 1445-1447.

19 Kinney, S. P., unpublished report.

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According to Sweetser			According to Kinney	
	Pounds	Cost	Pounds	Cost
Additional coke	41	$ 0.07	32	$0.055
Additional limestone	23	.015	43	.030
Slower production	--	.050	--	.040
Total	--	$ 0.135	--	$0.125

Mott and Wheeler[20] found that, according to theoretical calculations and data from blast-furnace practice in France and England, the coke equivalent of 1 percent ash is between 34 and 45 pounds, depending upon the fixed carbon in the coke. An average figure would be about 40 pounds or 2 percent of a short ton. This would amount to $0.07 if coke costs $3.50 per ton, which agrees very well with the estimates by Sweetser and Kinney. Louis[21] estimated that costs in addition to extra coke amount to $0.07 for each additional unit of ash.

Fieldner[22] has reported that coke made from washed coal has fewer cross-fractures, greater resistance to breakage on handling, and less small coke and breeze. It would be very difficult to determine the monetary saving as a result of the improved structure of coke made from washed coal.

Iron ore

Cost of smelting additional units of silica. - The removal of silica is the most important problem in concentrating iron ore. If the silica occurs as fine sand, it can be removed simply and cheaply. As the industry undertakes to remove silica from ores which are more difficult to concentrate the cost of concentration will probably increase. The economical limit of concentration will depend upon the cost of removing the silica and upon the saving in smelting the concentrated ore.

The actual cost of smelting iron ore containing varying percentages of silicon will depend upon a number of factors, such as cost of coke, ash, and sulphur in the coke, gas credits, and operating charges above raw materials which fluctuate with furnace output. As pointed out in the discussion of sulphur in coke, high-sulphur fuel normally requires a larger slag volume. In so far as possible high-silica ores should be allocated to plants with high-sulphur coke.

The cost per ton of pig iron of smelting an additional unit of silica in the ore will depend upon the following: (1) The additional coke required, (2) additional limestone required for flux, (3) increased transportation charges on units of iron, (4) decrease in output, and (5) slag disposal.

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20 See footnote 16, p. 147.

21 Louis, H., Discussion of paper by C. S. Gill, Effect of Varying Ash in the Coke on Blast Furnace Working: Jour. Iron and Steel Inst., 1927, vol. 116, p. 91.

22 Fieldner, A. C., Influence of Washing Coal on Coke Properties and on Gas and By-Product Yields; Rept. of Investigations, 3020, Bureau of Mines, May 1930, p. 12.

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It is obviously impossible to arrive at cost figures which will apply generally. However, an evaluation of these various items based upon assumed costs will illustrate how individual plants can arrive at figures for their own practice.

Additional coke.--It will require about 4,100 pounds of 51.5 percent iron ore to make 1 ton of pig iron. Each additional unit of silica in the ore - say, above 8.5 percent - will introduce 41 pounds of silica. The problem then is to determine how much additional coke, how much limestone, and what changes in production and transportation costs will result from this additional 41 pounds of silica. This quantity of silica will increase the slag volume 117 pounds per ton of pig iron if the slag contains 35 percent silica. Mott and Wheeler's[23] summary of the carbon equivalent of 1 pound of slag, as calculated by Evans and Bailey, Scott, Deladriere, Lilot, Clements, and Johnson, indicates that it requires about 0.29 pound of carbon to decompose the limestone for 1 pound of slag and to melt the slag. This is equivalent to 33 pounds of coke containing 88 percent fixed carbon. These theoretical values are based upon the heat generated in burning 1 pound of carbon to carbon monoxide in the tuyère zone; that is, they are based upon hearth heat requirements. No allowance has been made for the fact that as furnaces are operated 15 to 25 percent of the carbon charged is consumed in heat-absorbing reactions outside of the tuyère zone. A correlation of slag volume and fuel consumption of 30 American furnaces and 15 English blast furnaces indicates that 0.4 pound of coke is a conservative figure for the coke equivalent of 1 pound of slag. On this basis, 47 pounds of coke will be required for an increase of 41 pounds of silica or 117 pounds of slag. This extra coke will cost $0.08 at a price of $3.50 per net ton.

Additional limestone.--Forty-one pounds of silica will require about 60 pounds of calcium oxide or 113 pounds of 53 percent limestone. This quantity of limestone will cost $0.075, if limestone is worth $1.50 per gross ton.

Transportation on units of iron.--Transportation from the Mesabi range and items incidental thereto, including $0.05 interest and insurance charges, amount to $1.79 per ton of ore delivered at lower Lake ports, $2.69 delivered at Mahoning and Shenango Valleys, and $3.02 at Pittsburgh. The transportation charges on 41 pounds of silica will be $0.033, $0.05, and $0.055, respectively, for lower Lake ports, Shenango and Mahoning Valleys, and the Pittsburgh district. These figures show the desirability of allocating high-silica ores to Lake furnaces rather than to inland furnaces.

Decreased tonnage.--The reaction on this point might be that 47 pounds of coke would not necessarily slow production because the furnace could be blown faster to compensate for the increase in fuel consumption. However, the question arises as to why the furnace is not being driven faster if this is possible. Obviously the question of tonnage will depend upon a number of factors, including the immediate demand for pig iron. Normally, one would expect some decrease in tonnage as the coke increases.

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23 See footnote 13, p. 144.

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Brassert[24] has reported data showing the relation between coke consumption and tonnage for all furnaces at the South Works of the Illinois Steel Co. for 1911 and 1912. According to the record of these furnaces, each pound of additional coke decreases output by 0.2875 ton of iron per day. Therefore 47 pounds of coke would mean a daily decrease of 13-1/2 tons or 1.6 percent on a 800-ton furnace. Assuming that cost items amounting to $2.50 will increase directly as the tonnage decreases 1.6 percent, the additional cost due to smaller output will be $0.04 per ton of pig iron.

Slag disposal.--The disposition of additional slag, while of minor importance compared to other items, should be considered. In some cases slag is disposed of without cost, while in other cases a small charge is necessary. Since the item is small and conditions very no attempt will be made to estimate costs.

Summary of costs.--The increase in the cost of pig iron for each additional unit of silica in the ore may be summarized as follows:

Additional coke,	$0.080
Additional limestone,	.075
Additional transportation charges,	.053 to .055
Decreased tonnage,	.040
	0.228 to .250

Smelting costs per unit of silica in iron ore.--This increase in the cost of pig iron, amounting from $0.23 to $0.25, is distributed over 1.83 long tons of iron ore. Therefore on the basis of the prices which have been assumed the cost of each additional unit of silica per ton of ore will be from $0.125 to $0.135. Due to variations in costs and furnace practice this figure might range from 10 to 14 cents.

Size Preparation of Ores

Uniformity of size

The difficulty of charging fine iron ore and blast-furnace coke in such a way as to obtain layers of stock having uniform resistance to gas flow from the periphery to the center of the furnace has been shown by the Bureau of Mines in its investigations of actual conditions inside the blast furnace. Uniformity of size is the keynote to uniform gas distribution in the blast furnace. Obviously, attainment of perfect uniformity of ore size is too expensive to be considered. Investments in crushing and sintering processes undoubtedly soon come to the point of diminishing returns. The judicious use of sintering, crushing, and sizing, however, can doubtless be made to yield good returns in many cases. Furnace operators, as a whole, are very particular about the size of coke and limestone but continue to charge their

24 Brassert, H. A., Modern American Blast-Furnace Practice: Yearbook, Am. Iron and Steel Inst., 1914, p. 62.

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furnaces with large quantities of fine ore. Harrison[25] has demonstrated the practicability of sintering limonitic iron ores at the mine. In his opinion sintering will be restricted in the immediate future to ores with unfavorable smelting characteristics, to ores high in fines, to ores high in moisture which offer a substantial saving in transportation, and to ores which fall in a double penalty range. However, he sees interesting possibilities in screening out finer sizes of Mesabi ores, in sintering the fines, and in shipping a mixture of sinter and coarser sizes, provided a premium is granted for improved structure.

According to Craig[26] there are 20 washing plants, 4 crushing plants, 3 washing and jigging plants, 5 crushing and screening plants, 4 screening plants, 2 crushing and washing plants, 1 drying and crushing plant, 1 sintering plant, 1 magnetic concentrating plant, 1 washing and screening plant, and 1 washing, screening, and sintering plant on the Minnesota iron ranges. In 1930 about 40 percent of the total ore shipped from Minnesota was treated in some manner to improve the grade or structure or both. The major portion of the beneficiated ore is derived from washing plants and from crushing and screening plants. It should be possible to segregate a great deal of this ore into sizes at comparatively low cost. An important step from the standpoint of improving the structure would be to segregate the fine sizes from the washing plants. One plant is now shipping their bowl-classifier product separately and sintering it at the furnace. This seems to be a step in the right direction, inasmuch as the major part of this product is potential flue dust. Important amounts of recoverable fines are discharged into the tailings from washing plants. There has been little incentive for the ore producers to attempt to recover this fine material because of the limitations on the fines in the shipped ore. If the fine concentrates are segregated and sintered, further recovery of fines will not add potential flue dust to the ore shipped and detract from its physical structure. A great deal of progress has been made as a result of thorough sampling, chemical analysis, and grading of ores according to chemical composition. Many blast-furnace irregularities have no doubt been eliminated by the use of ores of more uniform analysis. If physical structure were given greater recognition in evaluating ores, much could be accomplished by the size preparation of iron ores.

Absolute size

The upper limit in the particle size of iron ore should be governed by resistance to size degradation in the furnace and by reducibility. In general, hard dense ores require longer time for reduction and break down less when subjected to mechanical action and heat. Such ores should be crushed to minus 2 inches. Fine ores which readily break down under the application of heat and mechanical shock can be greatly improved by sintering. Reducibility under laboratory conditions does not have great significance if an ore is so fine that it reaches the lower part of a blast furnace before coming in contact with sufficient gas to preheat it to reducing temperatures and to reduce it.

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25 Harrison, Perry G., Sintering Limonitic Iron Ores at Ironton, Minn.: Am. Inst. Min. and Met. Eng., Tech. Pub. 284, New York meeting, February 1930, 12 pp.

26 Craig, John J., Mining Directory of Minnesota: Bull. Univ. of Minnesota Sch. Mines Exp. Sta., 1931, pp. 192-193.

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Alumina in Iron Ores

A great many furnace operators are interested in obtaining ores which will add enough alumina to their burdens to allow them to produce slag containing about 14 percent alumina rather than 10 to 12 percent alumina. It is claimed that better control of sulphur is possible with the slags higher in alumina. Alumina tends to increase the temperature at which the slag reaches the hearth and also retards the descent of the iron globules through the slag, both of which would aid desulphurization. Substantial amounts of alumina are derived from coke ash, therefore as washed coal is used more generally, the demand for aluminiferous ores will probably increase.

Limestone

The amount of available calcium oxide, the size of the lumps, and uniformity are the three important characteristics of limestone. As the silica and alumina increase, the available calcium oxide decreases and the slag per ton and the coke per ton increase approximately as follows:

Limestone A (50% CaO, 5.5% Al_2O_3 + SiO_2)	Lb.	Limestone B (54% CaO, 1.5% Al_2O_3 + SiO_2)	Lb.
SiO_2 + Al_2O_3 from ore and coke,	500	SiO_2 + Al_2O_3 from ore and coke	500
SiO_2 + Al_2O_3 from limestone (5.5% x 1124 lb.),	62	SiO_2 + Al_2O_3 from limestone (1.5% x 952 lb.),	14
Total SiO_2 + Al_2O_3	562	Total SiO_2 + Al_2O_3	514
Total CaO (50% x 1124 lb.)	562	Total CaO (54% x 952 lbs.)...	514
Total slag per ton	1,124	Total slag per ton	1,028

Additional slag from limestone A (1,124 lb. - 1,028 lb.)	96
Additional flux when using limestone A (1,124 lb. - 952 lb.)	172

The foregoing shows that an increase of 4 percent SiO_2 plus Al_2O_3 in the limestone necessitates the use of 172 pounds more of flux and 96 pounds more of slag are produced. Ninety-six additional pounds of slag will increase the coke per ton by about 38 pounds (0.4 x 96) which, at $3.50 per ton, will amount to about $0.07 per ton of pig iron. Production would be slowed up about 1.2 percent on an 800-ton furnace, which would increase the cost above raw materials by about $0.03. Thus it can be seen that 4 percent silica plus alumina would add about 10 cents to the cost of a ton of pig iron due to the additional coke required and slower production.

If limestone costs $1.50 per gross ton, the fluxing charge would be $\frac{952}{2,240} \times \$1.50$ or $0.64. Due to the penalty of 10 cents for additional coke and slower production, the fluxing charge when using the lower-grade limestone is required, therefore the cost per gross ton should not exceed $1.08, if the high-grade limestone can be purchased for $1.50. The difference of $0.42 per gross ton of limestone is due to 4 percent more silica plus alumina.

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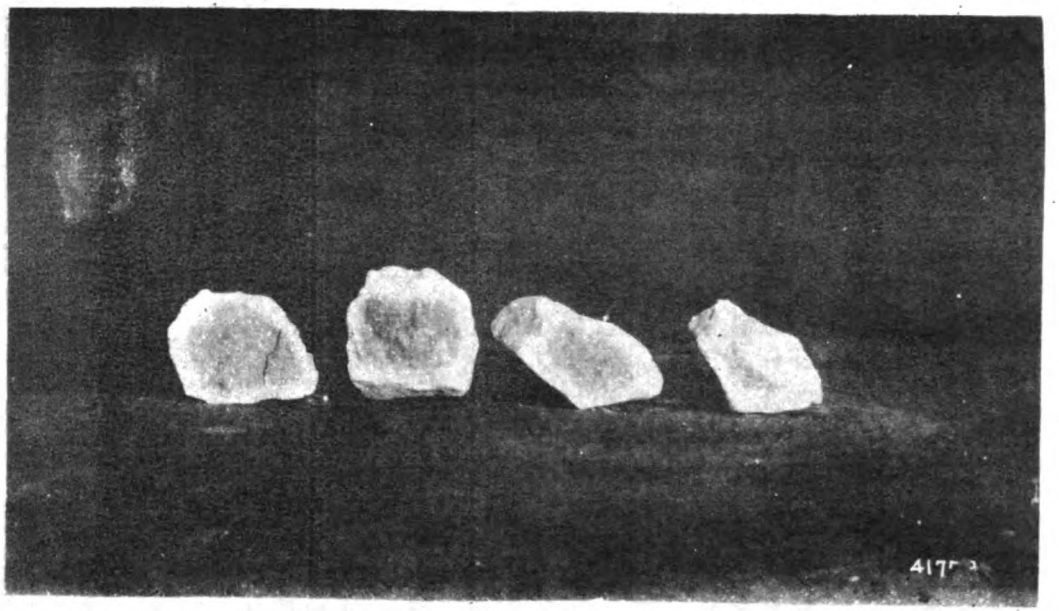

Figure 14.- Cross-sections of typical pieces of partly calcined limestone.

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It appears therefore that each percent of silica plus alumina in limestone decreases the value of limestone 10 cents per gross ton. Maccoun[27] states that each decrease of 1 percent silica between 5 and 1 percent reduces the value of limestone approximately 10 cents per ton.

Size of limestone

As a safeguard against fluctuations in silica and alumina as well as increasing amounts of these two elements furnace operators prefer larger sizes of limestone. Many operators prefer limestone ranging between 2 and 5 inches because size preparation eliminates fine material high in silica and alumina. If furnacemen could obtain the same quality and uniformity in smaller sizes of limestone, a great deal of prejudice against smaller sizes of limestone would probably disappear.

Furnas[28] found that calcination of limestone proceeds from the periphery of the piece toward the center along the phase boundary between the calcined and uncalcined parts of the piece. This phase boundary is shown in figure 14. The line of calcination advanced at a constant linear rate (measured in centimeters per hour) which increased with temperature but was independent of the size or shape of particle, degree of calcination, and previous heating. It is therefore a simple matter to compute the time required to calcine pieces of limestone of various sizes once the rate of advance of the line of calcination is known for various temperatures. Since the calcination proceeds from all sides of the piece toward the center, the size of the piece should be expressed as the average minimum cross section. The distance through which the line of calcination will advance will be one half of the average minimum cross section or thickness of the piece. For example, Furnas found that the line of calcination of the limestone used in his tests advanced at 0.69 centimeter per hour when the temperature surrounding the piece was 1,000° C. It would therefore require 8 hours to calcine a piece 11 centimeters thick ($\frac{5.5}{0.69} = 8$). These data indicate that pieces of limestone 3 to 4 inches thick (7.6 to 10.15 centimeters) reach the top of the bosh or lower before calcination is completed.

Limestone undergoes no size degradation before calcination. As the outside surface calcines the pieces probably undergo some reduction in size due to the mechanical action in the furnace. Unless it is known that a limestone breaks down readily after calcination there seems to be no reason for using 5- or 6-inch pieces of limestone. It seems probable that pieces of limestone of this size are not completely calcined until temperatures are reached at which the CO_2 evolved will readily attack the coke according to the following equation,

$$CO_2 + C \rightarrow 2\ CO.$$

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27 Maccoun, A. E., Recent Blast-Furnace Advancement: Blast Furnace and Steel Plant, vol. 49, 1915, p. 671.

28 Furnas, C. C., The Rate of Calcination of Limestone: Ind. Eng. Chem., vol. 23, May 1931, p. 534.

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The objection to this reaction is that carbon needed in supplying heat in the hearth is used up in a heat absorbing reaction above the tuyères. A limestone which breaks down readily after calcination should be used in larger sizes. Rate of calcination, which can readily be determined, and strength after calcination should govern the size, assuming that uniformity and grade can be maintained.

Dolomite

Opinions as to the relative merits of dolomite and calcite as flux vary widely. Bowles[29] has pointed out that the opinions of operators are often contradictory. McCaffery, Goff, Oesterle, Lorig, and Fritche[30] found that in general magnesia lowers the viscosity of blast-furnace slag and tends to smooth out changes in viscosity due to variations in composition. This stabilizing effect upon viscosity should, in their opinion, stabilize desulphurization, which would be true if there were no marked change in the chemical activity of the slag with variations in magnesia content. Although many opinions have been expressed on the merits of magnesia and lime in removing sulphur, systematic data supporting these opinions are lacking. McCaffery and his associates have contributed valuable information by showing the effect of magnesia upon slag viscosity. To apply their data, however, more information is needed upon the effect of viscosity upon desulphurization and silicon reduction.

Factors to be Considered in a Blast-Furnace Enterprise

Supply of raw materials

A supply of coking coal is of first importance in a blast-furnace enterprise. Analyses of coal indicates suitability from the standpoint of ash and sulphur, but information on coking quality and on by-product yields requires extensive small-scale tests which should be followed by oven tests. The investigation by Marshall and Bird[31] of coals from Pierce County, Wash., illustrates the type of experimental work which is necessary to investigate the suitability of coal for making blast-furnace coke. Their investigation was divided into three parts, consisting of a geological survey of the coal property, washing and crushing tests of the coal, and coking and by-product tests.

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29 Bowles, Oliver, Utilization Problems of Metallurgical Limestone and Dolomite: Am. Inst. Min. and Met. Eng., Tech. Pub. 62, February meeting, 1928, pp. 6-7.

30 McCaffery, R. S., Goff, I. N., Oesterle, J. F., Lorig, C. H., and Fritche, O. O., Viscosity of Blast-Furnace Slags: Am. Inst. Min. and Met. Eng., Tech. Pub. 383, February meeting, 1931, pp. 6-11.

31 Marshall, S. M., and Bird, B. M., Agglutinating, Coking, and Byproduct Tests of Coals from Pierce County, Wash.: Bull. 336, Bureau of Mines, 1931, 31 pp.

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The grade of iron ore and limestone which can be used will depend upon transportation charges and the cost of coke. A comparison of blast-furnace practice in Alabama and in the Northern States using Lake ores will show how transportation charges affect the grade of material which may be used. Coking coal, iron ore, and flux occur in the Birmingham district along a belt about 75 miles long. According to Crane[32] the Alabama iron ores have the following percentage composition: Iron, 34.36 to 36.41; lime, 15.74 to 19.1; silica, 9.68 to 12.78; alumina, 2.75 to 3.38; phosphorus, 0.267 to 0.325. Lake Superior iron ores had an average percentage composition for 1930 as follows: Iron, 51.33; silica, 8.7; phosphorus, 0.095; manganese, 0.82; moisture, 10.92. Operators in the Birmingham district use an ore containing about 15 percent less iron than Lake Superior ore. This means more ore, higher slag volume, and more coke per ton of pig iron. Due to the favorable location of raw materials in the Birmingham district, southern operators are able to compete with those in the North because lower costs of raw materials assembled at the blast-furnace plant compensate for lower-grade iron ore and a somewhat lower grade of flux.

Markets

Pig iron.--The size of a furnace can be varied within certain limits to meet the market for pig iron. The most recent single furnace plants have a capacity from 400 to 500 tons per day or from 140,000 to 175,000 tons per year. Construction of smaller furnaces is questionable from an economic outlook.

Gas.--Steel mills offer an outlet for large quantities of blast-furnace and coke-oven gas. In the case of a single furnace plant, operated independent of steel mills, a market for excess blast-furnace and coke-oven gas is an important item.

Coke.--A market for coke that is too small for blast-furnace use adds to the economic outlook of a single furnace plant.

Capital outlay

The Bureau of Mines has received many inquiries about blast-furnace enterprises from people who have no idea of the cost of building a single blast-furnace plant. Single-furnace plants will cost 4 to 5½ million dollars, depending upon the size and location of the plant and many other factors.

SUMMARY

The blast furnace is a heat generator, a gas producer, a heat interchanger, a deoxidizing chamber, and a melting furnace. Ore, which is the source of the iron, limestone, which is used as a flux, and coke, which is used as a fuel, are charged into the top of the furnace by means of a bell

32 Crane, W. R., Iron Ore (Hematite) Mining Practice in the Birmingham District, Ala.: Bull. 239, Bureau of Mines, 1926, p. 13.

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and hopper. Large volumes of hot carbon monoxide and nitrogen are generated by burning coke in small zones in front of the tuyères, through which preheated air is admitted. As the coke is gasified in the combustion zones around the periphery of the furnace the charge descends under the force of gravity. Heat generated at the tuyères is carried to upper levels of the furnace by the rising gas stream, which gives up heat to the solid stock as the gas moves along a tortuous path formed by the voids in the charge. The gas stream follows the path of least resistance which is through that portion of the stock which contains the greatest effective free area for passage of the gas. The downward movement of the stock is affected by the location of the combustion zones in which the coke is being gasified. Since these zones are located around the periphery of the furnace, the stock settles faster along the walls than in the center.

The upper part of the furnace is a heat interchanger and a deoxidizing chamber. The efficiency with which heat is acquired by the stock and the efficiency with which oxygen is removed from the iron ore by hot carbon monoxide gas depend upon the opportunity for gas-solid contact provided in the size preparation of raw materials and in methods of charging.

The Bureau of Mines investigations of its experimental blast furnace and several industrial furnaces show that uniformity of size as well as absolute size have a pronounced effect upon the gas distribution in the blast furnace. An unrealized degree of nonuniformity in temperature, in gas flow, and in gas composition in the upper part of the furnace is due partly to size segregation at the stock line and partly to furnace lines. Although the charge may contain 35 percent voids only a part of the space is available for gas flow. The sizing of ore and the charging of three sizes (medium, fine, and coarse) separately have proven an effective means of obtaining more uniform gas flow, lower fuel consumption, and increased output. Such a practice can readily be adopted if about one half of the ore is larger than one half inch. For the fine ores in the Lake Superior district, steps toward agglomeration will have to accompany sizing of the ore. Segregation of fine concentrates and sintering at the furnaces are steps which have been taken by one company toward better size preparation of the ore.

The physical characteristics of coke have first importance. Coke, which has a low bulk density in the furnace, is very desirable. This implies low ash content, uniformly large pieces with no breeze or small sizes to fill the voids, and maximum porosity without sacrificing resistance to abrasion and to size degradation in handling. Sulphur and ash in coke detract from its value. If an operator is forced to use siliceous ores or to charge gravel to build up slag volume to handle sulphur, each additional percent of sulphur will add from 14 to 20 cents to the cost of pig iron. Various estimates indicate that each percent of additional coke ash will add about 13 cents to the cost of producing a ton of pig iron.

The economical limit of concentration of iron ore will depend upon the cost of removing the silica and upon the saving in smelting the concentrated ore. Due to variations in costs of raw materials and in the sulphur in the coke the cost of each additional unit of silica per ton of ore will range from 10 to 14 cents and should be calculated for each set of conditions.

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The value of fluxing limestone depends upon available calcium oxide above that required to flux the silica and alumina in the limestone, upon the size of the lumps, and upon uniformity in composition. Each additional percent of silica plus alumina in fluxing limestone will decrease its value by about 10 cents per ton. Blast-furnace operators prefer larger sizes of limestone because the size preparation results in more uniform limestone of better grade.

Although many opinions have been expressed about the merits of magnesia and lime in removing sulphur systematic data are lacking. Viscosity measurements by McCaffery and his associates show that in general magnesia tends to lower and stabilize the viscosity. The optimum viscosity for aiding the desulphurization of the iron and silica reduction are not known.

A supply of coking coal is of first importance in a blast-furnace enterprise. The grade of all raw materials which may be used will depend upon transportation charges in assembling them at the furnace site. A market for about 140,000 to 175,000 tons of pig iron should be available. Markets for small-size coke and excess blast-furnace and coke-oven gas add to the economic outlook of a single merchant pig-iron furnace. The cost of a single furnace plant will range from 4 to 5½ million dollars.

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